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The BETTER Model for Cheatham Lake

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BETTER, a two-dimensional mathematical water quality model, was used to simulate water quality conditions in the main body of Cheatham Lake. Sources and preparation of input data, including reservoir and outlet geometry, meteorological conditions, model coefficients and inflow quality and quantity, are described. The report also outlines revisions to the model for the Cheatham application and calibration and verification procedures.

Three years, 1985-1987, were simulated under observed conditions, and model predictions were compared to observed data. Additional simulations were performed to estimate impacts on water quality resulting from 1) increasing the effluent from sewage treatment plants, 2) high dissolved manganese concentrations in the releases from J. Percy Priest Dam, and 3) a local storm event. Knowledge gained from simulations with the model is summarized and recommendations for future applications are made.

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The BETTER Model for Cheatham Lake

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The BETTER Model for Cheatham Lake

INTRODUCTION

The BETTER reservoir water quality model was applied to the entire length of Cheatham Lake using information from the annual years 1985, 1986 and 1987. The model was calibrated with the 1985 data and verified with 1986 and 1987 data. The model is now ready for use in making evaluations of water quality in Cheatham Lake. It is capable of simulating flow patterns, retention times, wind mixed depth, temperature, a tracer, suspended sediment, five-day BOD, dissolved oxygen, nitrogen, total phosphorus, surface CO_2, pH, algae, and dissolved manganese in two-dimensions which are reservoir length and depth. Data are input as daily average values and output values are likewise daily average values. A typical annual simulation requires between 15 and 17 minutes of CPU time on a VAX 8800 computer.

DESCRIPTION OF THE BETTER MODEL

Modeling of Cheatham Lake began with a version of BETTER which had been developed for Old Hickory Lake by Brown (1986). The report by Brown (1986) contains a user's manual which adequately describes the model which was the basis for the Cheatham application. Better is a two-dimensional reservoir water quality model that considers flow, mixing, temperature, stratification and residence time patterns as the basis for nutrient and dissolved oxygen simulations. The model reservoir is divided longitudinally and vertically into an array of volume elements so that gradients in water quality caused by inflows and vertical temperature stratification can be simulated. The model uses a daily time step. Flow patterns are functions of inflow/outflow, reservoir geometry, outlet depth, inflow temperature, and matched density deflections within the reservoir during stratification. Mixing is related to flow turbulence, wind speed, and surface cooling. A heat budget is used for surface heating and cooling. Suspended sediments are simulated with constant particle settling and light attenuation is a function of suspended sediment concentrations. Dissolved oxygen patterns are modeled by considering the sources and sinks within the reservoir including reaeration, photosynthesis, respiration, inflowing BOD, and sediment oxygen demand (SOD). Nutrients, including nitrogen, phosphorus and inorganic carbon are a part of algal growth simulations. The carbonate system is included as a part of the modeling.

The model uses a geometric representation of Cheatham Lake consisting of 19 columns and 9 layers for a total of 171 volume elements. Between the Cheatham Dam (CRM 148.7) and the confluence of Mill Creek (CRM 194.4), the cells are all approximately 3 miles long. There are 15 of these 3 mile long cells. Above Mill Creek, there are 4 columns which are approximately 6 miles long. Nine layers of 5 foot thickness extend from elevation 390 downward to 345. The geometric representation is shown by Figure 1. The cell volumes (vl), cell upper surface areas (ac), and downstream conveyance areas (ai) are entered into arrays in the input geometry files which are CHG85.DAT, CHG86.DAT and CHG87.DAT.

Eight inflows and one outflow are used for the model with the stipulation that there can be only one inflow per column of cells. Starting at the most upstream column (19), the first inflow is the Old Hickory Dam release, followed in a downstream direction by the

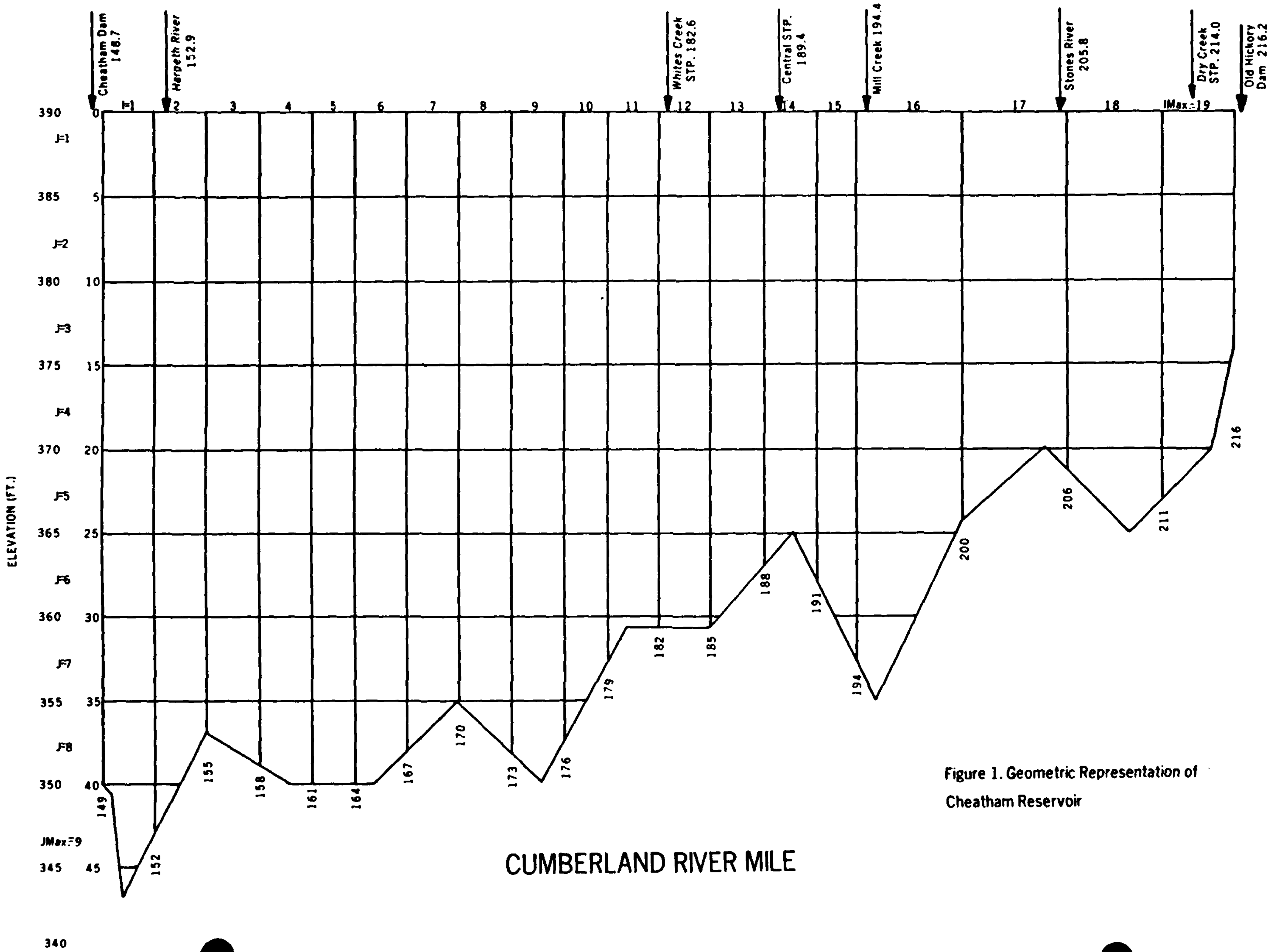


Figure 1. Geometric Representation of Cheatham Reservoir

Dry Creek wastewater effluent into column 18, (this avoids two inflows into Column 19) the Stones River into column 17, Mill Creek into column 15, (rather than its position at the end of column 16), Nashville Central wastewater effluent into column 14, Whites Creek wastewater effluent into column 12, and the Harpeth River into column 2. The other inflow is local inflow which is input into each column based upon drainage areas. The local inflow to Cheatham Lake is based upon the hydrology of Richland Creek and input to each cell based upon the percent of drainage area for each cell to the total drainage. Local is calculated by GCHIN8X.FOR.

More specifically, it was determined that Richland Creek flows are representative of local runoff patterns. This was determined by comparing Richland Creek stream flows to Harpeth River and Sycamore Creek flows for 1985 through 1987.

Mill Creek daily flows were calculated within Enable spreadsheets as a function of the ratio between Mill Creek and Richland Creek drainage areas (108 and 28 square miles respectively) as noted in equation (1).

$$\text{Mill Creek Flow} = 3.83 \times \text{Richland Creek Flow} \quad (1)$$

Local inflows were calculated by multiplying the Richland Creek flows by a ratio of Richland Creek to local drainage areas (805 square miles) as shown in equation (2).

$$\text{Local Flow} = 28.5 \times \text{Richland Creek} \quad (2)$$

When these estimated local inflows did not match the back-calculated total inflows, adjustments were made to the Old Hickory inflow in order to preserve the more realistic local inflow pattern provided by Richland Creek stream flows.

The use of the three wastewater discharges as modeled inputs of municipal/industrial wastes was deemed appropriate based upon a review of all NPDES discharger permits between Cumberland River Mile 217 on Old Hickory Lake and the Cheatham Dam. Table 1 shows these discharges and it is obvious that the Nashville Central Sewage Treatment Plant, STP, (design flow ≈ 98.7 MGD), the Whites Creek STP (design flow = 25 MGD) and the Dry Creek STP (design flow = 12.3 MGD) are the major point sources of pollution to Cheatham Lake.

Outflows from Cheatham Lake were modeled by a single discharge point at elevation 370 ft. Because Cheatham Lake will not be stratified when spilling, this was considered a realistic model simplification and assumption.

Necessary input data to the model are nine lines containing flows and water quality for each day of simulation. The first line contains the Cheatham outflow, dry bulb temperature, dew point, wind speed and solar radiation. The second line contains the Old Hickory flow, temperature, SS, DO, pH, alkalinity, algae, detritus, dissolved organic matter, NH_3, NO_3, total PO_4 and dye. The third line contains the Dry Creek flow and quality and this continues until all eight inflows are entered. The input data file is quite large as each day takes 9 lines including 110 data entries. A yearly file contains 3,285 lines of 40,150 data entries. These data files are named CHIN85.DAT, CHIN86.DAT and CHIN87.DAT. BETTER simulations require two input files, CHG8X.DAT and CHIN8X.DAT; a command file, CH8X.COM; and the BETTER Model, CHBETR.FOR. The model creates three output files which are CHBETR.BIN, DAYPLOT8X.OUT and CHPRNT8X.OUT. The file CHBETR.BIN is a binary file

Table 1

NPDES Permits Between Cumberland River Miles 149 and 217
on Cheatham and Old Hickory Lakes According to TDHE

Discharger	CRM	Flow (MGD)	Type	Effluent Criteria (BOD/SS/NO_3)
Ashland City STP	158.2	0.370	Sewage	30/-/1.0
Cheatham County Industrial park	162.5	0.075	Sewage	30/-/1.0
State Industry	158.2	0.0	--	--
Amoco Oil	183.4	0.0	--	--
Ashland Petroleum	190.5	0.0	--	--
Citgo Petroleum	191.4	0.0	--	--
Cumberland U.D. WTP	--	0.0	Sludge	--
Dundee Cement Co.	--	0.0	--	--
Dupont	--	0.0	--	--
Exxon Corp.	--	0.0	--	--
Ford Motor Co.	--	0.0	--	--
Lion Oil Co.	189.8	0.0	--	--
Madison U.D. WTPP	200.3	0.0	--	--
Marathon Oil	185.1	0.0	--	--
Metro Ready Mix	189.1	0.0	--	--
Mo. Portland Cement	182.0	0.0	--	--
Nashville Central STP	189.2	98.7	Sewage	10/5/5
White's Creek STP	182.6	25.0	Sewage	10/5/1.0
Dry Creek STP	213.9	12.3	Sewage	30/-/1.0
Old Hickory U.D. WTP	--	0.0	--	--
Old Hickory U.D. STP	206.1	1.0	Sewage	30/-/1.0
Stauffer Chem. Co.	184.0	0.0	--	--
Triangle Refineries	--	0.0	--	--
Laroche Steel	182.8	0.0	--	--
Old Hickory Dam	216.2	0.0	--	--
Hendersonville Shop. Cntr.	215.9	0.020	Sewage	30/5/1.0
COE Powerhouse, Rockland	216.3	0.0	--	--
White House U.D. WTP	215.7	0.0	--	--
Ergon, Inc.	193.3	0.0	--	--

containing output at 5 day intervals and is used for plotting the output data. DAYPLOT8X.OUT is a file of selected parameters to be used for plotting times-series graphs. CHPRNT8X.OUT is a file which can be printed out up to 30 days per year for visual checking of the input and output. Plotting programs are available for presenting the model output.

INPUT, CALIBRATION AND VALIDATION DATA

The ENABLE software package was used extensively for database management in the Cheatham Lake water quality modeling project. The Cheatham project is data rich. It is unusual to have such a large amount of water quality and flow data available. Following is a list of data sources incorporated into the model:

1) Metropolitan Nashville weekly river survey (testing 10 water quality parameters at 13 locations between CuRM 174.2 and 214.0).
2) Metropolitan Nashville Wastewater Treatment Plants daily water quality data (daily water quality measurements of effluent at Central, Whites Creek and Dry Creek plants, including flows).
3) Harrington Water Treatment Plant (daily water quality of intake water from Cheatham).
4) USGS - U. S. Department of the Interior (flow measurements on three local streams, dam releases, and water quality from Old Hickory dam releases).
5) U. S. Corps of Engineers (reservoir elevations, flows, and periodic river survey measurements of water quality).

All of the afore mentioned data were entered, using ENABLE, in the DBMS (Database Management System). After data were entered, spreadsheets were developed for various purposes, including development of a water budget for the reservoir, compilation of data files used by the BETTER model, and listing of data by date and river mile used for verification of the model's output.

Over 65,000 bits of data were entered in ENABLE, taking 250 hours of entry time. All work was performed on an IBM compatible 286 AT personal computer equipped with a 10 MB hard drive, 360k floppy drive and 640k RAM working memory. The ENABLE package itself takes roughly 1.4 MB of fixed disk space. Any work files created will take up more fixed disk space. ENABLE works fairly well with the 640k working memory, but its spreadsheet functions are limited with very large spreadsheets, incorporating mathematical computations within the spreadsheet.

There are systems available with expanded memory that would enhance ENABLES's spreadsheet capabilities. Moreover, using a PC equipped with math coprocessor will cut work time about 90%.

Data were entered using the floppy drive (A: drive on our system). This method is slower than using the hard disk, but is safer from a working standpoint. After data entry on a floppy disk, data can be backed up on a master disk for added protection and then stored on the fixed disk.

In the Cheatham Lake project, data followed the route shown below, but this route is not limited to our specific application:

Raw Data >>> Storage in Database (DBMS) >>> Retrieved Data Placed on Spreadsheet >>> Spreadsheet Saved as Word Processing File >>>

Word Processing Files Transferred to Mainframe Computer or Sigma Plot Directory for Model Runs and Graphics

As mentioned previously, spreadsheets were also formed for verification of the model output and mass balance calculations. Spreadsheets are also used to gather data that the modeler wishes to display graphically.

ENABLE's graphics are oriented to business applications, therefore, another software package was incorporated for graphics. Sigma Plot was selected because of its high performance, versatility and low cost.

Following is a list of data bases that were created for the Cheatham model, including the field names. Few restrictions, with respect to minimum and maximum values, field length, etc., were placed on the data. The following databases are in ready to use form, with corresponding input forms listed:

Database	Input Form	Description	Fields	Form
RIVERRUN	RRI	Metro Nashville Weekly Survey 1985-1987	CURM	NNN.N
			YEAR	YY
			MODAY	MM/DD
			DO	NN.N
			AVGTEMP	NN
			BOD	NN.N
			SS	NNN
			AMMONIA	N.NN
			CL	NNN.N
			ALK	NNN
			PHOS	N.NN
			PH	N.N
			FECCOLIF	NNNN

****

HWPD	HWP	Harrington Water Plant Data 1985-1987	DATE	MM/DD
			YEAR	YY
			TEMP	NN
			RAWTURB	NNN
			RAWALK	NNN
			RAWPH	N.N

****

FLOWZ	FLOWZIN	Tributary and storm water flows 1985-1987	DATE	MM/DD
			YEAR	YY
			LOCATION	XXXXXXX
			FLOW	NNNNN.N
			FLOWCFS	NNNNN.N
			MILLFLOW	NNNNN.N

****

NWWTP	WWDS	Metro Nashville Wastewater Trmt. Plant daily data (Central, Whites Creek and Dry Ck) 1985-1987	PLANT	XXXXXXX
			MODAY	MM/DD
			YEAR	YY
			FLOW	NNN.N
			BODRAW	NNN.N
			BODEFF	NN.N
			SSRAW	NNN
			SSEFF	NNN
			NH3RAW	NN.N
			NH3EFF	NN.N
			FECALCOL	NNNN

****

WWPMAVG	WWMAVG	Wastewater plant monthly avgs for Central, Whites Ck and Dry Ck plants 1985-1987	MO	MM
			YEAR	YY
			PLANT	XXXXXXX
			FLOW(MGD)	NNN.N
			BODR	NNN
			BODP	NNN
			BODS	NNN
			BODF	NNN
			SSR	NNN
			SSP	NNN
			SSS	NNN
			SSF	NNN
			TKNR	NN.N
			TKNP	NN.N
			TKNS	NN.N
			TKNF	NN.N
			NH3R	NN.NN
			NH3P	NN.NN
			NH3S	NN.NN
			NH3F	NN.NN
			PO4R	NN.NN
			PO4P	N.NN

			PO4S	N.NN
			PO4F	N.NN
			DOF	NN.N

****

HICKQUAL	HICKQUAL *	Old Hickory Dam water quality USGS 1985-1987	DAY	(1-365)
			YEAR	YY
			DO	NN.N
			PH	N.N
			TEMP	NN.N

*NOTE: It is easier to give the database and input form the same name, as in the HICKQUAL database. The file name extension is used to differentiate between various types of files e.g., dbs=database, wpf=word processing file).

****

CENTRALS	CENTRALN	Central Plant storm water quality and flows 1985-1987	DATE	MM/DD
			YEAR	YY
			FLOW	NNN.N
			BOD	NNN.N
			NH3	NN.N
			SS	NNN
			DO	NN.N
			PH	N.N
			SETSOL	NNN
			FECCOLI	NNNN

****

Running the BETTER model with output printed for days on which river run surveys were made allows verification in several ways. Model output can be compared directly with field data from the river run, Old Hickory releases, Harrington water plant intake data and the Corps of Engineers river survey (periodic).

Notice that data are grouped by fields. Reports can be produced, or files can be displayed according to conditions set by the user. Since there are daily records labeled by mo/day, year and Cumberland River mile, records may be displayed for any particular day, year, CuRM, or any combination of groups of the conditions set.

Other data required for modeling were placed upon the VAX 8800 system. These data included the Cheatham elevations and outflows, meteorological data for 1985, 1986 and 1987 (DEW8X.DAT, DRY8X.DAT, SOLAR8X.DAT and WIND8X.DAT) and the geometry files (CHG8X.DAT).

The purpose of the file system used was to allow each individual file to stand alone so that revisions could be made to any one file without changing some massive and perhaps intimidating input file. All of the various input sub-files are merged during each run by a fortran program named GCHIN8X.FOR into the master file CHIN8X.DAT described earlier. For example, GCHIN86.FOR opens and reads files for the Cheatham flows (CHEAT86.OUT), the Old Hickory flows and water quality (OLHICK86.WPF), Dry Creek sewage treatment flows and quality (DRYCK86.WPF), Stones River flows and quality (STONES86.WPF), Mill Creek flows and quality (MILLCK86.WPF), Central Sewage Treatment flow and quality (CENT86.WPF) White Creek Sewage Treatment flows and quality (WHITES86.WPF), Harpeth River flows and quality (HARP86.WPF), and the four meteorological data files (DRY86.DAT, DEW86.DAT, WIND86.DAT, SOLAR86.DAT). The data from these 12 files is manipulated into the major time-varying data file for the model (CHIN86.DAT). All files with the file name extension .WPF are word processing files which were developed using ENABLE. This system makes editing files much easier.

RUNNING BETTER FOR CHEATHAM

The file map required for running the Cheatham version of BETTER is shown by Figure 2. For 1985, 1986 and 1987, all input files are available and have already been processed by GCHIN8X.FOR to produce

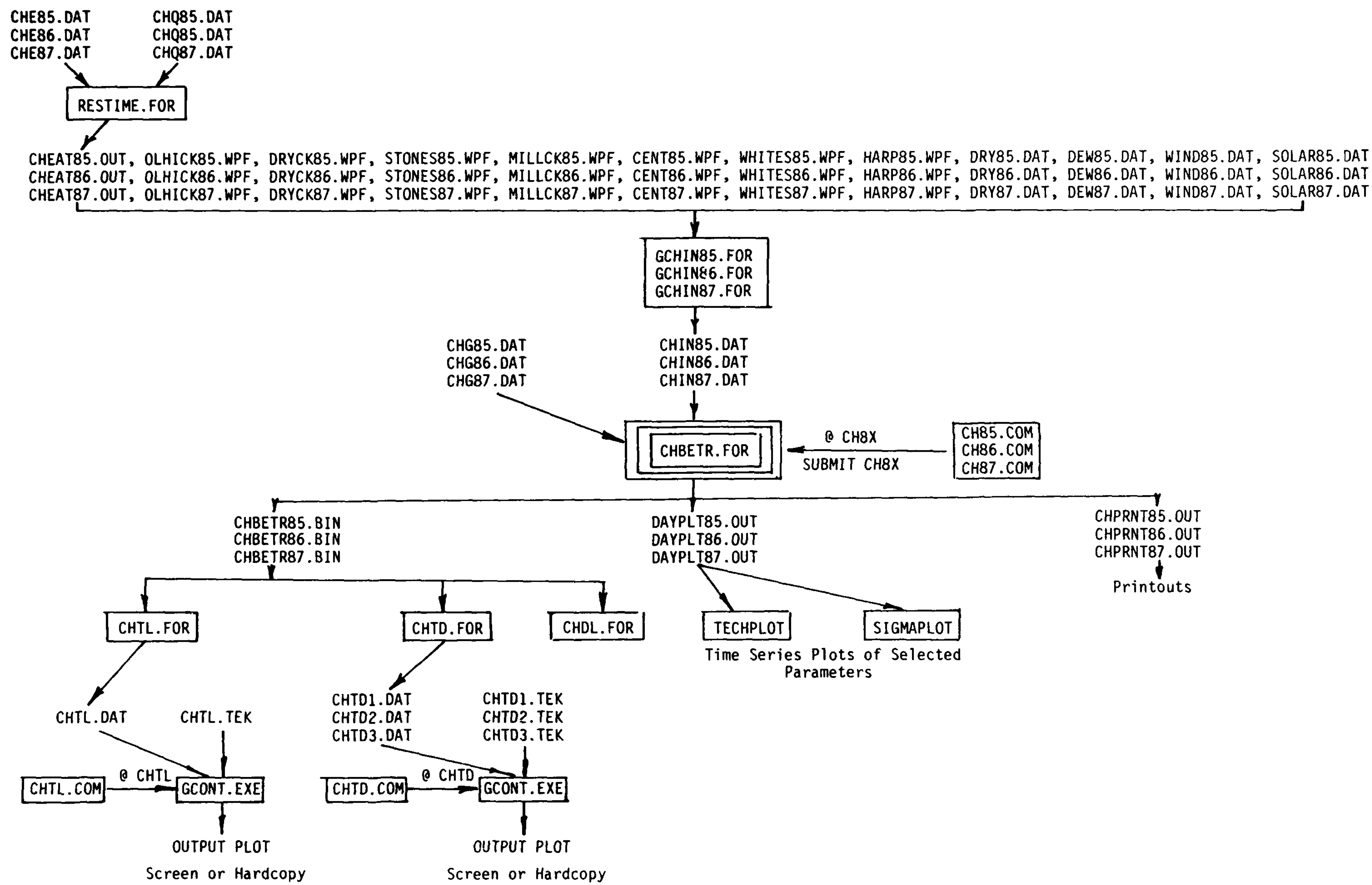


Figure 2. Data and Program Map Used for the Cheatham Version of BETTER

the time-varying data file CHIN8X.DAT. The geometry and control data files CHG8X.DAT are also available. The commands necessary to run CHBETR.FOR on a VAX machine are either @CH8X or SUBMIT CH8X (S30 CH8X is a shortened version of submit). If the run command is @CH8X, the terminal displays the run as it progresses and ties up the terminal for the duration of the run. The SUBMIT CH8X command is, of course, a batch run. Runs are requiring between 15 and 17 minutes of CPU time for simulations of one year.

The model output can be studied from the CHPRNT8X.OUT file. Time-series of the output can be plotted using TECHPLOT or SIGMA PLOT from the DAYPLT8X.OUT file. Special purpose plots are possible using the time-length plotting file CHTL.FOR; the time-depth file CHTD.FOR or the depth-length file CHDL.FOR.

CHEATHAM MODELING WITH BETTER - THE DEVELOPMENT PROCESS

The development process for adapting the modified version of Old Hickory BETTER (Brown, 1986) was straight-forward. All initial calibration was performed using the data from 1985. Then runs were made for 1986 and 1987 for verification. The objective was to get a good match between model simulations and field data using constant parameters for all three years.

More than 50 runs were necessary to accomplish the previous objective. The variable DC, vertical mixing, was varied on 16 runs between 1 and 2 yielding a final value of 1.1. The variable FDFAC, Froude factor, was varied 9 times between 0.1 and 5 yielding a final value of 0.1. The variable WDFAC, wind factor, was varied 18 times between 0.75 and 1 yielding a final value of 0.85. The variable SOD, sediment oxygen demand, was varied 5 times between the values of 0.25 and 0.75 for a final value of 0.25. After 28 runs, it was determined that a turbulent reaeration term was needed for proper DO simulation. The Churchill formula for turbulent stream reaeration was added to BETTER (Churchill, et al., 1962).

The increase in dissoved oxygen from reaeration caused by both wind and water velocity is calculated as:

$$\Delta DO = O2KL * (SATO - DO) * AI * DT/VO \qquad (3)$$

where:
- ΔDO = increase in DO due to reaeration
- DO = dissolved oxygen concentration (mg/l)
- SATO = saturated DO (mg/l)
- O2KL = oxygen transfer rate (ft/day)
- AI = seqment surface area (ft^2)
- DT = time step (days)
- VO = segment volume (ft^3)

The Churchill formulation for O2KL is:

$$O2KL = 5.0 * Velocity/Depth^{.0667} \qquad (4)$$

where:
- Velocity = water velocity (ft/sec)
- Depth = water depth (ft)

Thus, the DO increase due to aeration is a function of the difference between the current DO level and saturation, the reaeration rate parameter, the segment surface area and the ratio of the time step to the segment volume. The reaeration parameter is related to the water velocity and the reciprocal of depth to the 2/3 power.

The current implementation allows reaeration of the surface segment only; mixing with deeper layers occurs at the end of the model timestep (end of each day). Some additional field data and model comparisons are required to determine if reaeration is properly simulated for Cheatham Lake.

The next fifteen runs were necessary to set values of DC, FDFAC, WDFAC and SOD which work in concert with the reaeration algorithm. The final coefficient values are given in Table 2.

It was not very difficult to take the Old Hickory version of BETTER and apply it to Cheatham. The goodness of fit of model output to actual field data was performed visually using tabulations and graphical analyses for the 1985 runs. When it was noted that all parameters were satisfactorily modeled for 1985, the years 1986 and 1987 were simulated. Similar graphical and visual comparisons led to the conclusion that the model was verified by the 1986 and 1987 field data. No parameter adjustments were made after seeing the 1986-1987 simulations. Figures 3 through 11 are typical time-series plots used to visually assay the capabilities of Cheatham BETTER for temperature and DO. The reader is encouraged to study Figures 3-11 to see the capabilities of the model.

The goodness of fit of the three years of simulation was assessed statistically for 7 variables and four stations using the SAS program. The seven variables available from the Nashville Metro river run surveys were temperature, dissolved oxygen, suspended solids, pH, ammonia, total phosphate and BOD_5. These parameters were compared to the

Table 2

Final Coefficient Values used for the Cheatham Version of BETTER
(Also see Brown, 1986, Appendix I)

Parameter	Code	Value
Sediment oxygen demand	SOD	0.25 grams/m^2·day for all columns
Vertical mixing coefficient	DC	1.1
Wind mixing fraction	WCOEF	0.03
Turbidity vs. Extinction coefficient	TUREX	0.05/m
Density deflection	FDFAC	0.10
Withdrawal zone factor	QTH	1.0
Min. light ext.	EXTMIN	0.25/m
Evaporation	EVFAC	1.0
Windspeed adjustment	WDFAC	0.85
Light coefficient	PARFAC	.50
Algae vs. Light	ALGEXT	0.1
Min. element vol.	VMIN	0.2 (1000 ac. ft.)
Withdrawal adjustment	FDOUT	1.0
Algae max. growth	TPMAX	2.0/day
Algae max. respiration	PRESP	0.1/day
Algae max. mortality	PMORT	0.01/day
Algae settling rate	ASET	0.1 m/day
Light half-sat.	PS2L	30.0 kcal/m^2·hr
Carbon half-sat.	PS2C	0.01 mg/l
Algae phos. content	ALGAP	0.004
Algae nitrogen content	ALGAN	0.06
Algae carbon content	ALGAC	0.4
Algae min. temp.	ALGT 1	5°C
Algae opt. temp.	ALGT2	15°C
Algae opt. temp.	ALGT3	25°C
Algae max. temp.	ALGT4	35°C
Algae growth factors	TK1	0.1/day
Corresponding to	TK2	0.98/day
Temperatures	TK3	0.10/day
	TK4	0.10/day
Detritus carbon	DETRC	0.4
Detritus nitrogen	DETRN	0.06
Detritus phosphorus	DETRP	0.004
Detritus settling rate	DSET	0.1 m/day
SS settling rate	SSSET	0.3 m/day
Detritus temp. decay	DETT1	0°C
Detritus temp. decay	DETT2	30°C
Dissolved org. decay	DORDK	0.1/day
Max. nitrification rate	CNH_3DK	0.050/day
Max. detritus decay	DETUDK	0.125 day
DOR min. temp.	DORT1	0°C
DOR max. temp.	CNH3TZ	30°C

Table 2 (cont.)

Parameter	Code	Value
Nitrification O_2 ratio	O2NH3	4.7 mg O_2/mg DET
Detritus decay O_2	O2DET	1.0 mg O_2/mg ALG
Algae respiration O_2	O2RESP	1.6 mgO_2/mg ALG
Photosynthesis O_2	O2FA	0.2 mg C/mg DOR
Anaer. NH_3 release	ANH_3	0.2 gN/m^2·day
Anaer. PO_4 release	APO4	0.0 gP/m^2·day
Anaer. denit. rate	ANO3DK	0.15/day
Anaer. DOR release	ADOR	0.0 g DOR/m^2·day

FIGURE 3

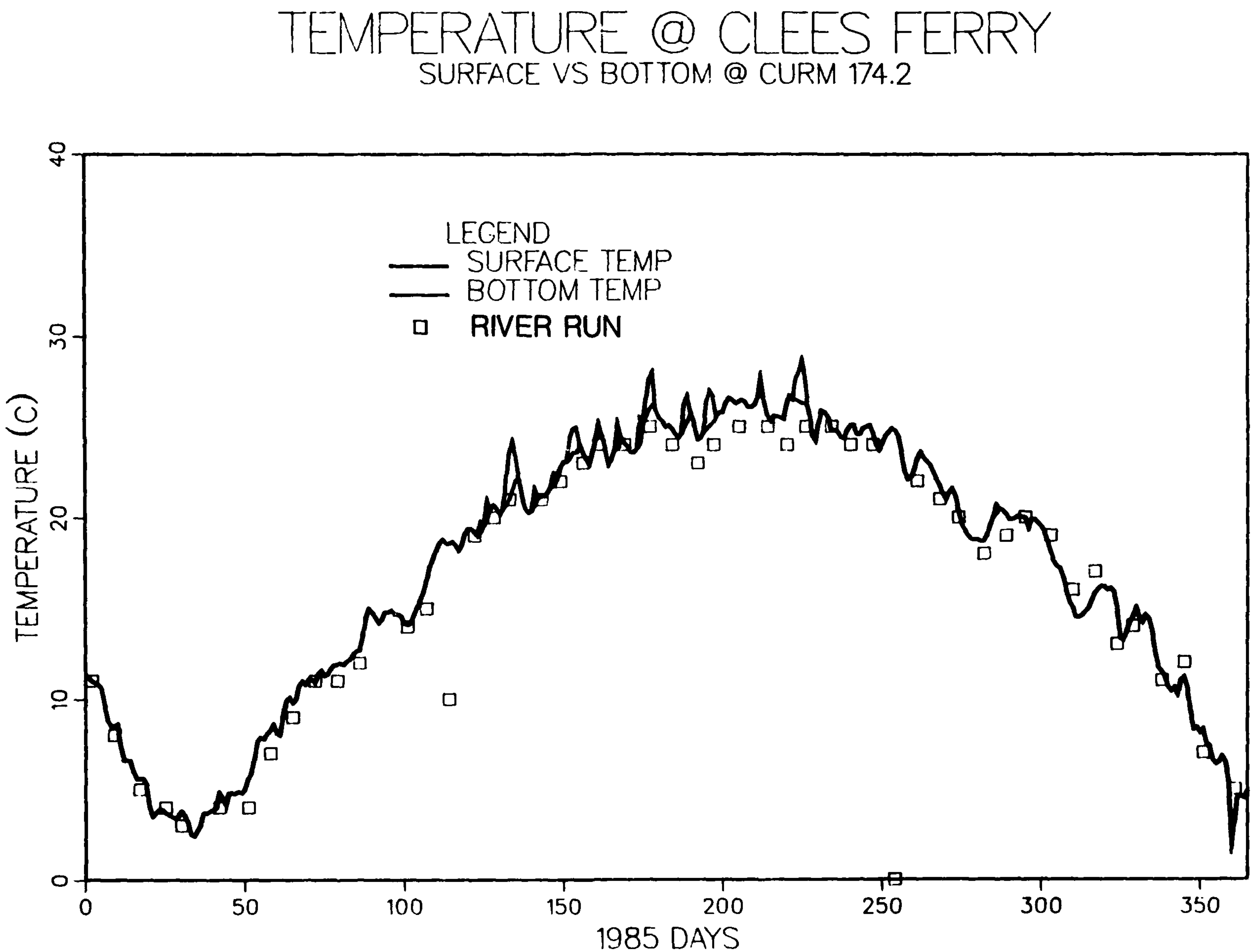

TEMPERATURE @ CLEES FERRY
SURFACE VS BOTTOM @ CURM 174.2
LEGEND
SURFACE TEMP
BOTTOM TEMP
RIVER RUN
TEMPERATURE (C)
0
10
20
30
40
1985 DAYS
0
50
100
150
200
250
300
350

FIGURE 4

TEMPERATURE @ CLEES FERRY

SURFACE VS BOTTOM @ CURM 174.2

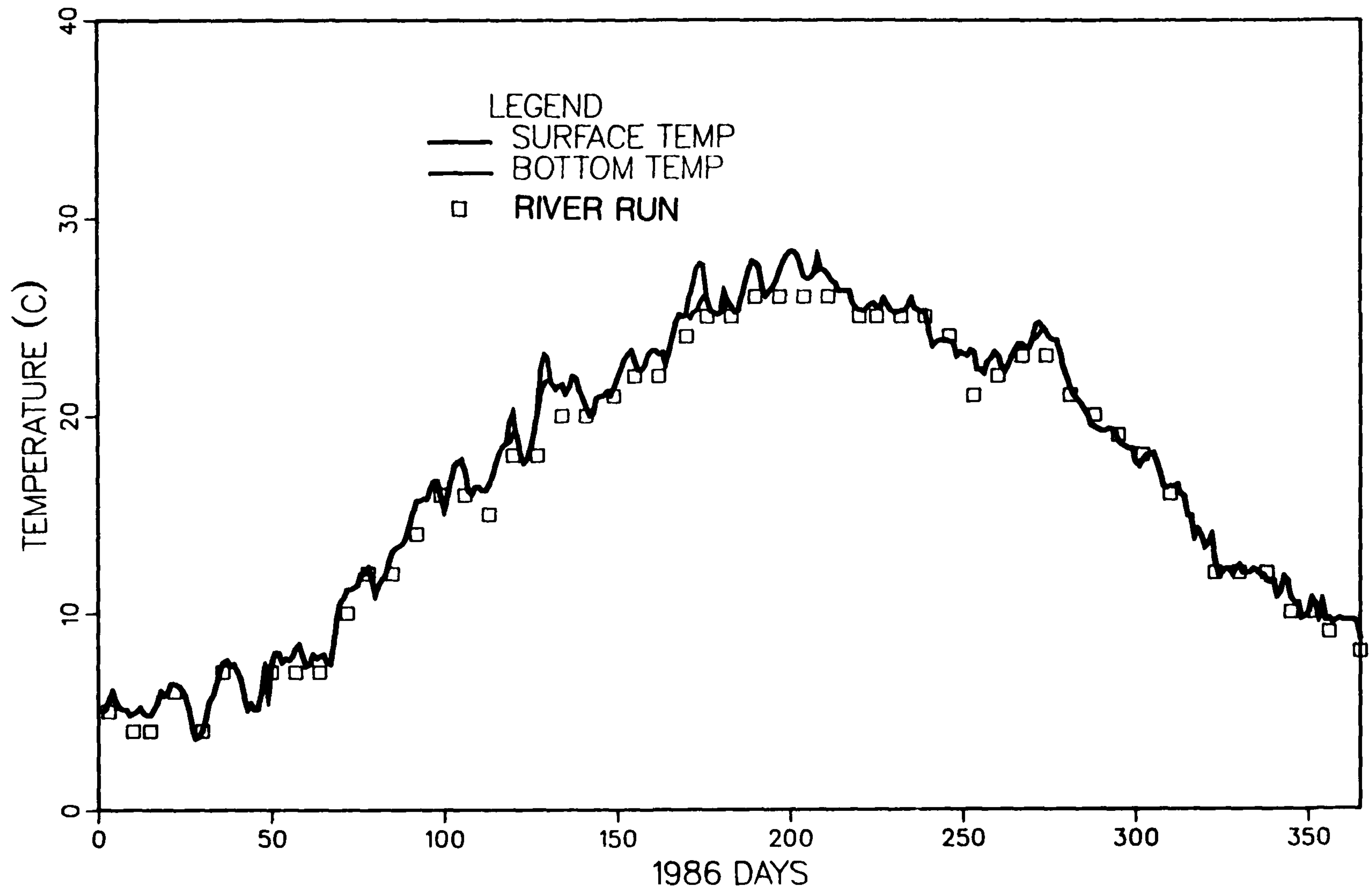


FIGURE 5

TEMPERATURE @ CLEES FERRY

SURFACE VS BOTTOM @ CURM 174.2

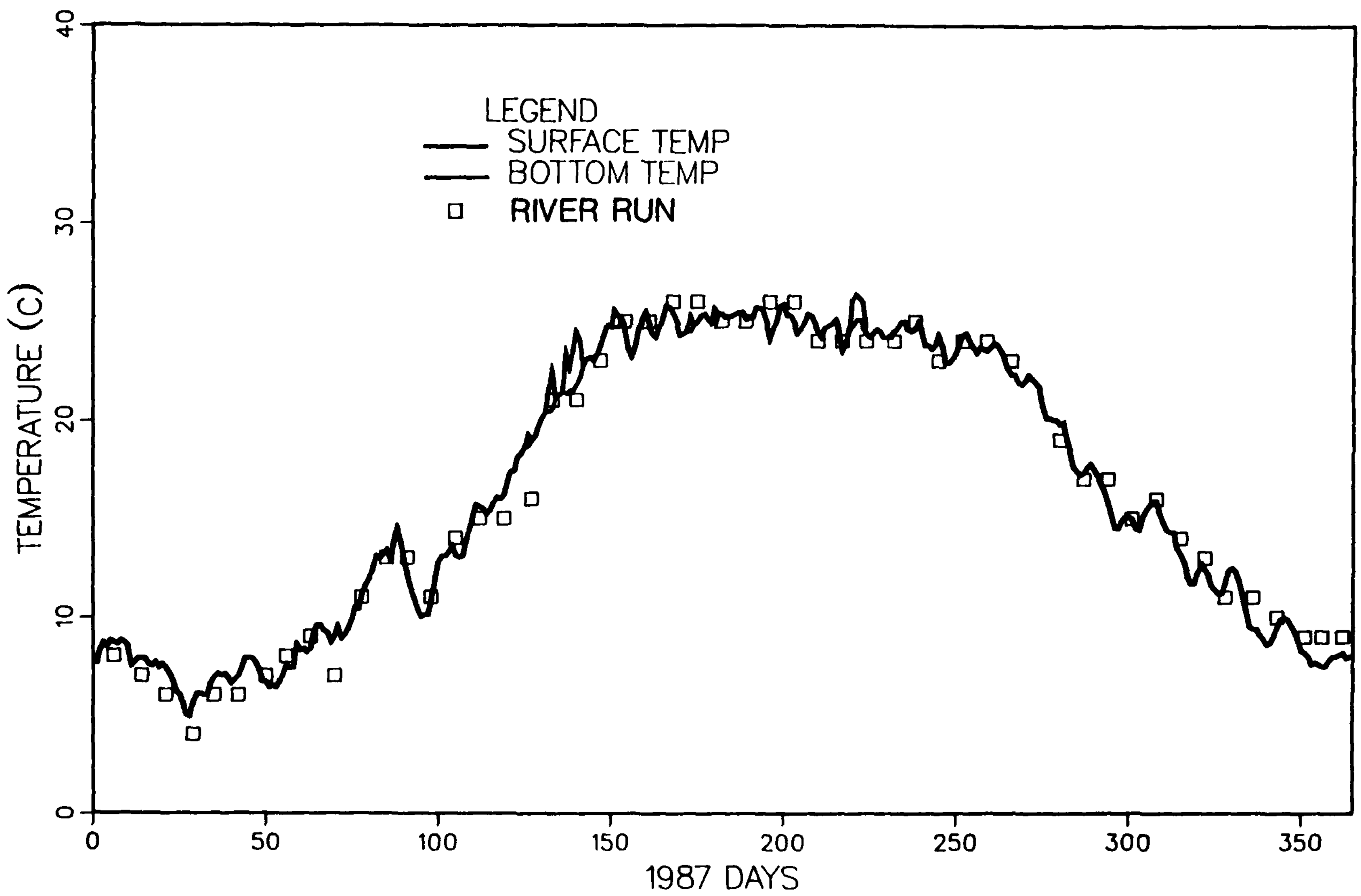


FIGURE 6

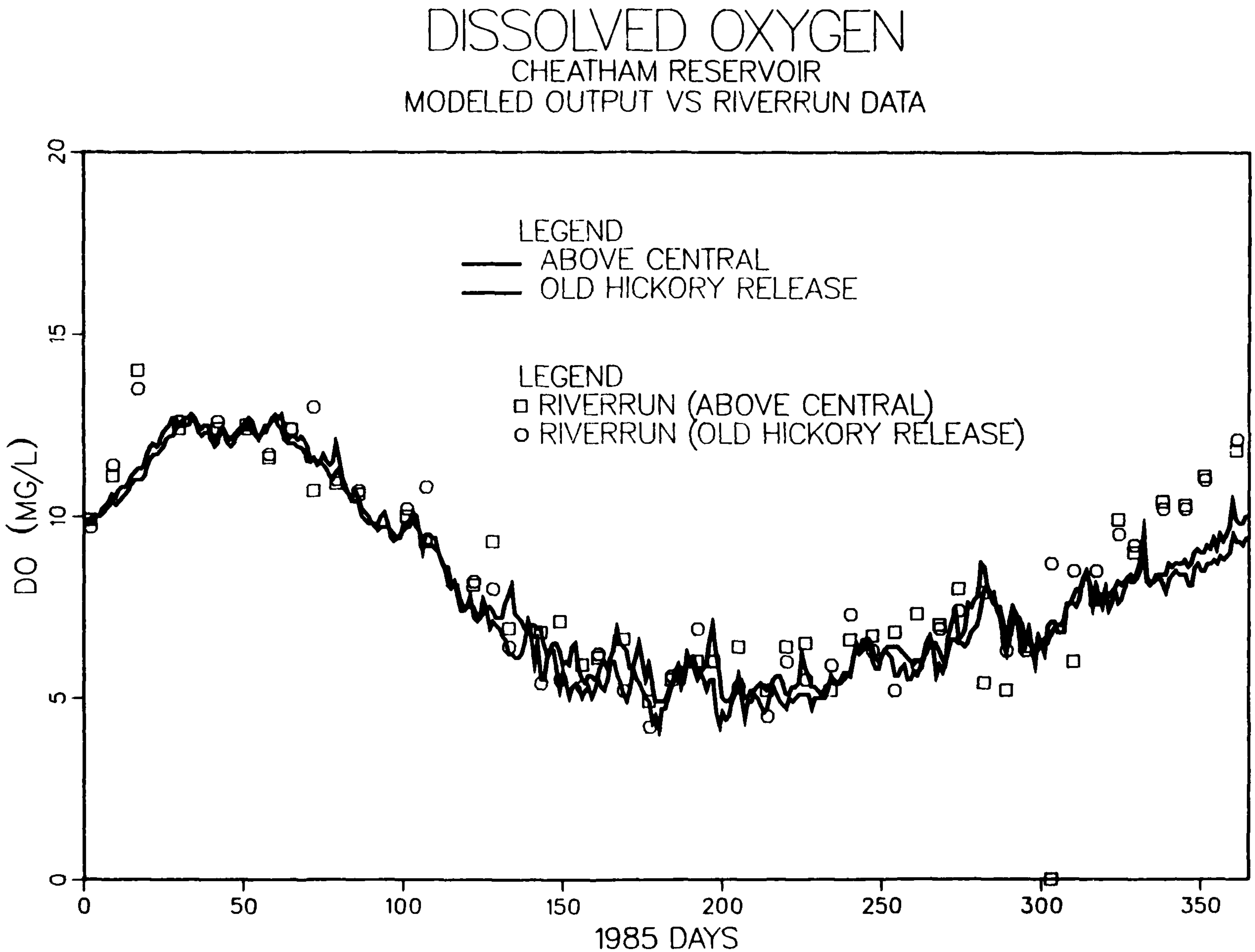

DISSOLVED OXYGEN
CHEATHAM RESERVOIR
MODELED OUTPUT VS RIVERRUN DATA
LEGEND
ABOVE CENTRAL
OLD HICKORY RELEASE
LEGEND
RIVERRUN (ABOVE CENTRAL)
RIVERRUN (OLD HICKORY RELEASE)
DO (MG/L)
0
5
10
15
20
0
50
100
150
200
250
300
350
1985 DAYS

FIGURE 7

DISSOLVED OXYGEN

CHEATHAM RESERVOIR

MODELED OUTPUT VS RIVERRUN DATA

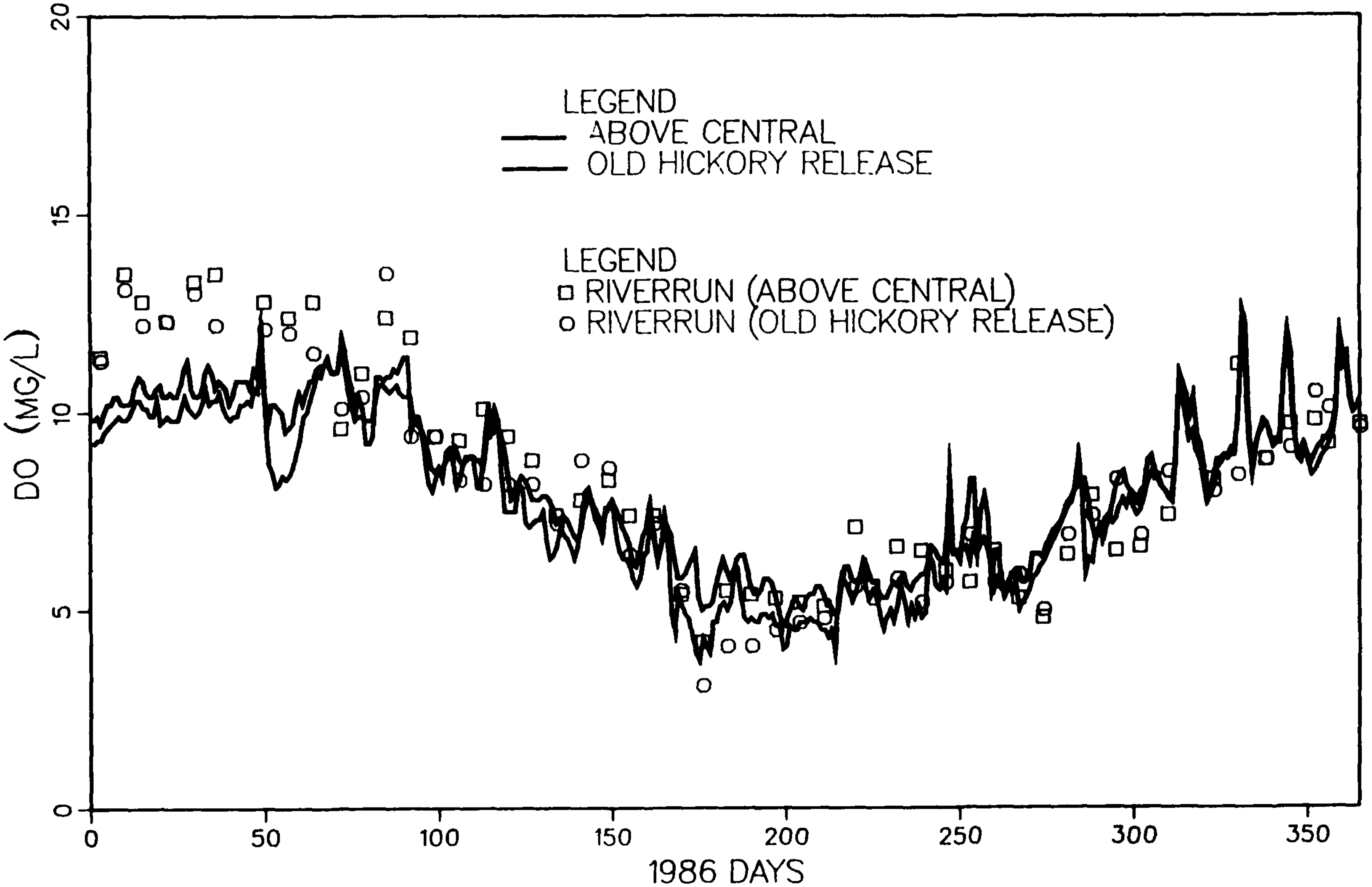


FIGURE 8

DISSOLVED OXYGEN
CHEATHAM RESERVOIR
MODELED OUTPUT VS RIVERRUN DATA

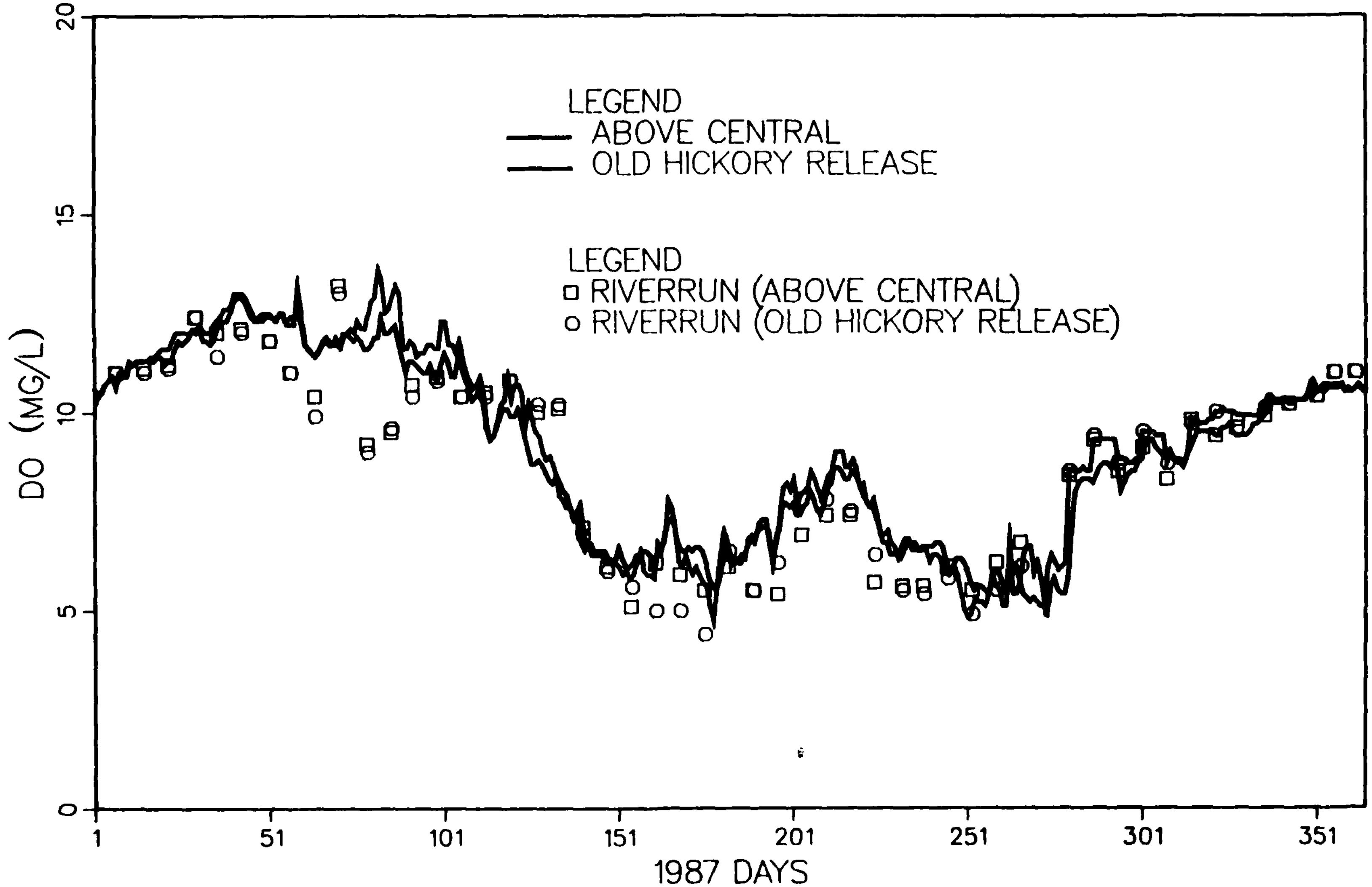


FIGURE 9

DISSOLVED OXYGEN @ CLEES FERRY

SURFACE VS BOTTOM @ CURM 174.2

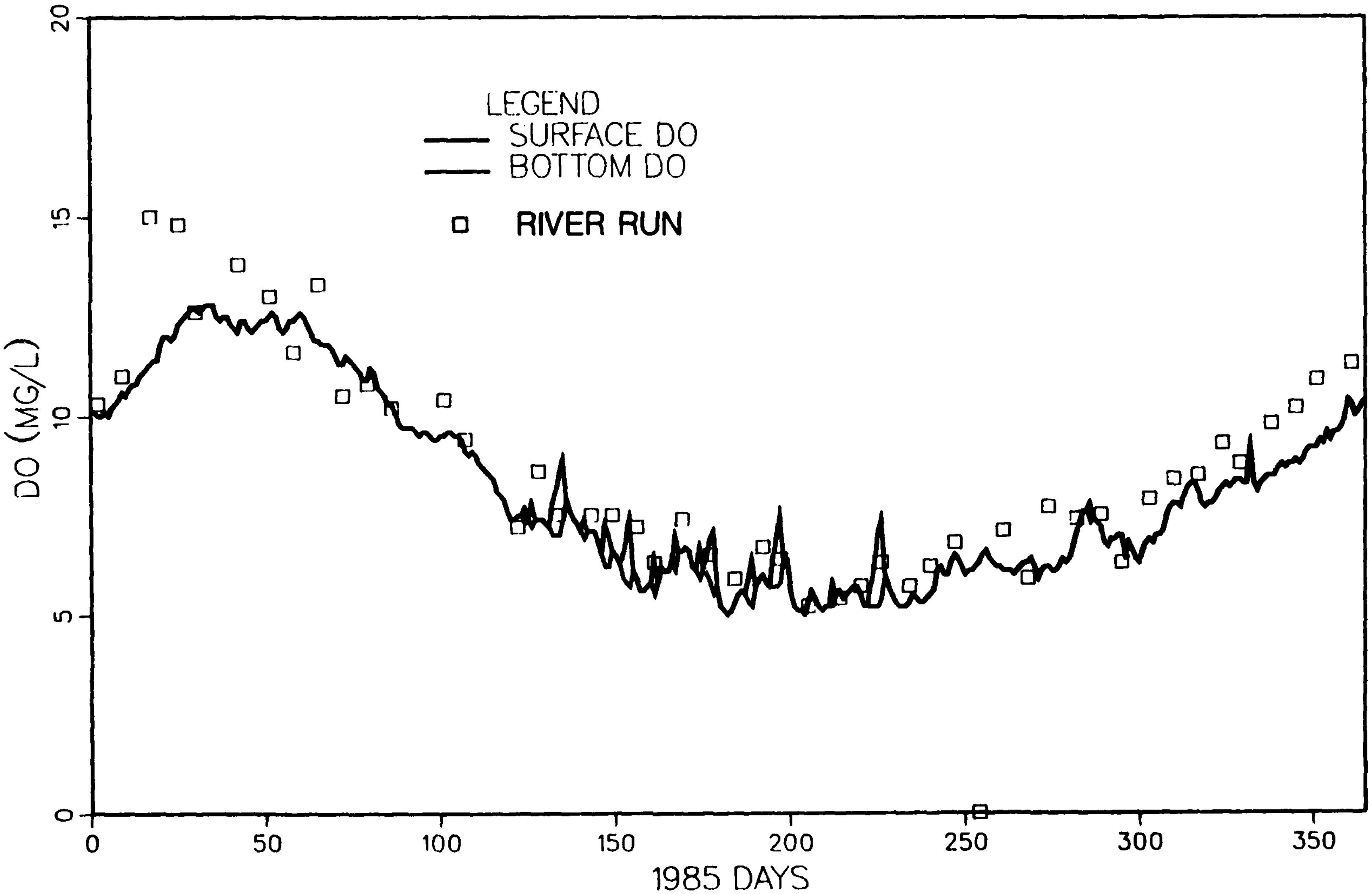


FIGURE 10

DISSOLVED OXYGEN @ CLEES FERRY

SURFACE VS BOTTOM @ CURM 174.2

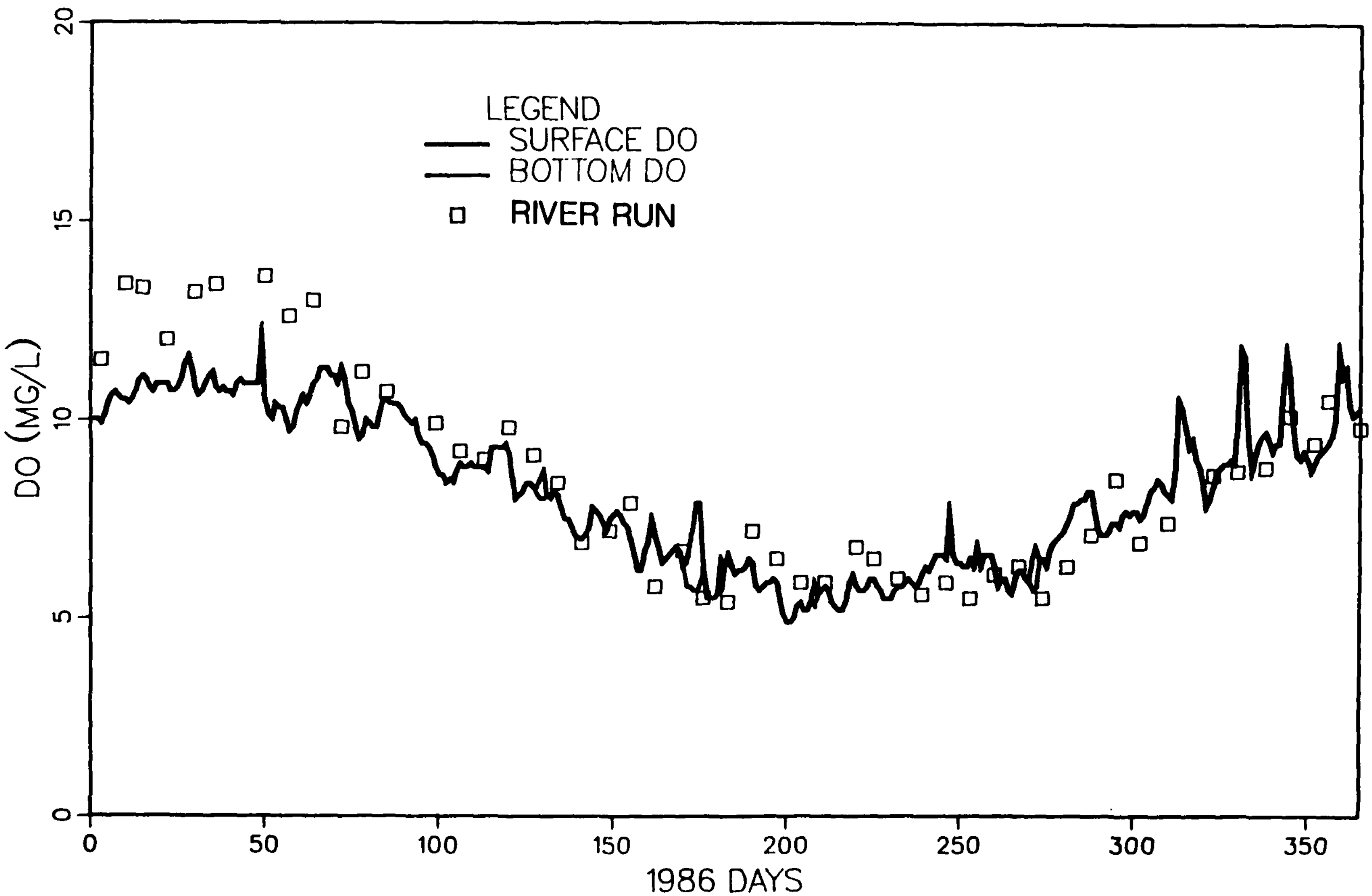
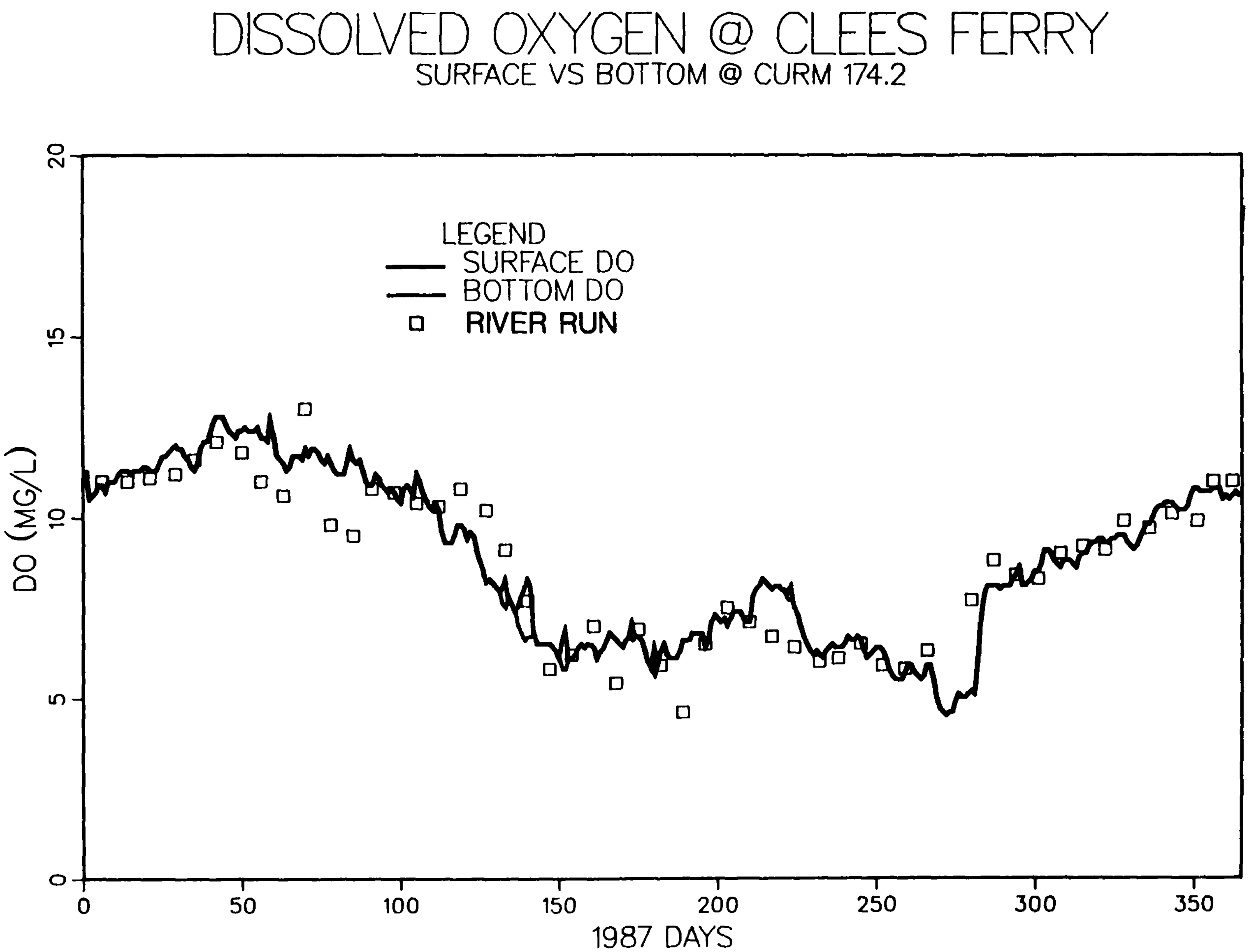


FIGURE 11


DISSOLVED OXYGEN @ CLEES FERRY
SURFACE VS BOTTOM @ CURM 174.2
LEGEND
SURFACE DO
BOTTOM DO
RIVER RUN
DO (MG/L)
0
5
10
15
20
0
50
100
150
200
250
300
350
1987 DAYS

predicted values at four locations which were the Old Hickory tailrace, the Stones River confluence, the Nashville area (column 14) and the Clees Ferry area (column 9). In each case, the data collected by Metro were compared to model output for an entire year. Since Metro runs the river weekly, there are about 50 data pairs for each year for each parameter. The SAS program computed Pearson correlation coefficients for each parameter for each year. Values of the Pearson correlation coefficient near unity indicate a strong correlation while those near zero indicate a poor linear correlation.

Table 3 summarizes the Pearson coefficients for the Cheatham version of BETTER. The values are useful in evaluating the performance of the model, in evaluating the reliability of the input and river run data and in highlighting problem areas. Table 3 shows that BETTER is very good at predicting temperature and dissolved oxygen for Cheatham. BOD predictions are fairly good but deteriorate in the downstream direction. Suspended solids predictions are sometimes erratic but overall performance of the model is fair. Field data for suspended solids are often erratic and can reflect wind and wave action on shoreline areas, barge traffic, unmodeled tributary inflows and upwelling flows within the reservoir. Thus a strong correlation is not likely.

Input pH values were taken from the U.S.G.S. monitor at Old Hickory Dam. During 1985 and 1986, there was only poor to fair correlation between the U.S.G.S. monitor values and the Metro river run values. During these years, BETTER was able to start with poor input and improve the pH simulations. The ability of BETTER to simulate pH is rated fair to good. The ability of BETTER to model ammonia is fair while

Table 3

Correlation Coefficients (R) Between Predicted and Observed Values for Cheatham Lake

		Reservoir Location			
Year	Parameter	Old Hickory	Stones River	Nashville	Clees Ferry
1985	Temperature	0.996	0.994	0.994	0.993
1986	Temperature	0.995	0.996	0.992	0.994
1987	Temperature	0.991	0.993	0.989	0.998
1985	Dissolved Oxygen	0.915	0.902	0.900	0.941
1986	Dissolved Oxygen	0.885	0.926	0.910	0.886
1987	Dissolved Oxygen	0.925	0.927	0.900	0.922
1985	Suspended Solids	0.999	0.095	0.326	-0.106
1986	Suspended Solids	0.998	0.647	0.521	0.486
1987	Suspended Solids	0.999	0.372	0.360	0.442
1985	pH	0.241	0.404	0.427	0.335
1986	pH	0.429	0.551	0.589	0.565
1987	pH	0.999	0.875	0.261	-0.024
1985	NH_3	1.000	0.447	0.195	0.333
1986	NH_3	0.937	0.479	0.432	0.303
1987	NH_3	0.999	0.414	0.163	0.365
1985	Total PO_4	1.000	0.866	0.689	0.667
1986	Total PO_4	0.983	0.757	0.235	0.089
1987	Total PO_4	1.000	0.842	0.445	0.244
1985	BOD_5	0.962	0.734	0.633	0.476
1986	BOD_5	0.995	0.481	0.444	0.301
1987	BOD_5	0.988	0.826	0.712	0.433

its capability to model total phosphorus must be rated as good. Overall, the model is quite good in handling these parameters including BOD. There was a fair correlation of predicted-observed BOD values. At the present stage of BETTER, BOD is not actually modeled in a direct manner. Organic material is divided into dissolved organic matter and detritus and these two are directly modeled. An approximate BOD is output from a presumed combination of these two and calculated as an oxygen demand at 20°C for 5 days. This is a close simulation to a laboratory measured BOD_5,20C. Of course, BOD values are only ± 20 percent, at best when measured in the laboratory.

Statistical analyses were complemented by studies of time-series plots of the model predictions and the Metro river run results for all seven parameters and all three years. These time-series plots are shown as figures AI-1 through AI-42 in Appendix I. Each group of three year-figures are described by a page preceding each years results. The reader is encouraged to carefully examine the time-series plots as they are the visual portrayal of the calibration and verification process.

APPLICATIONS OF THE CHEATHAM MODEL

Following the setup, data collection, calibration and verification of the Better Model for Cheatham Lake, several applications of the model were made. These applications are presented in the following sections.

Hydraulic Residence Time

Reservoirs serve as large-scale water quality treatment reactors. The overlying factor governing how much treatment can be expected is the hydraulic residence time. For riverine systems, the corresponding parameter is flow. BETTER predicts the cumulative residence time of water parcels as they travel from Old Hickory Dam to Cheatham Dam and these times are printed on the output file CHPRNT8X.OUT.

Water residence time is so important to an understanding of water quality that an analysis was made of it from 1959 to 1987. Plots of reservoir residence times and flows are shown as figures 1-29 of Appendix II. Most hydraulic residence time values for Cheatham are less than ten days and the general range of values is between 2 and 10 days. In an effort to ascertain periods of low flow in a quantitative manner, a ranking of Cheatham Lake flows was made for the period of record for 1,2,3,4,...,30 day consecutive low flow periods. The results of this study are shown by Table 4. The average flows reported in Table 4 would be interpreted as average flows for x-number of consecutive days over 28 years of record. The 1-day average low flow occurred in 1960 at 600 cfs, the 2-day in 1969 at 885 cfs, the 3-day in 1969 at 1210 cfs and the 4-day in 1971-72 at 1433 cfs. Table 4 also shows that 1968 and 1969 were the years having long periods of low flow.

Low flow values are necessary for assessing reservoir dilution ratios for wastewater or stormwater inputs and for establishing contaminant concentrations. However, the transport and fate of these contaminants is related to the processing which takes place during the hydraulic residence time. The controlling parameter is the hydraulic residence time. For example, a 1-day low flow has little effect upon

Table 4

Average Low Flows for Consecutive-Day Periods for Cheatham Lake for the 1959-1987 Time Period.

No. of Consecutive Days	Year	Average Flow (CFS)
1	1960	600
2	1969	885
3	1969	1210
4	1971&72	1433
5	1969	1620
6	1969	1728
7	1968	1821
8	1968	1811
9	1968	1803
10	1968	1797
11	1969	1994
12	1969	2069
13	1969	2272
14	1969	2407
15	1969	2450
16	1969	2426
17	1969	2421
18	1969	2503
19	1969	2584
20	1969	2518
21	1969	2510
22	1969	2499
23	1969	2490
24	1969	2470
25	1969	2517
26	1969	2560
27	1969	2571
28	1969	2583
29	1969	2546
30	1969	2539

the reservoir if followed by high flows which would flush the system. For Cheatham Lake, water quality problems are most likely when the hydraulic residence time exceeds 10 days. Then, the reservoir is likely to stratify and begin processing water quality accordingly.

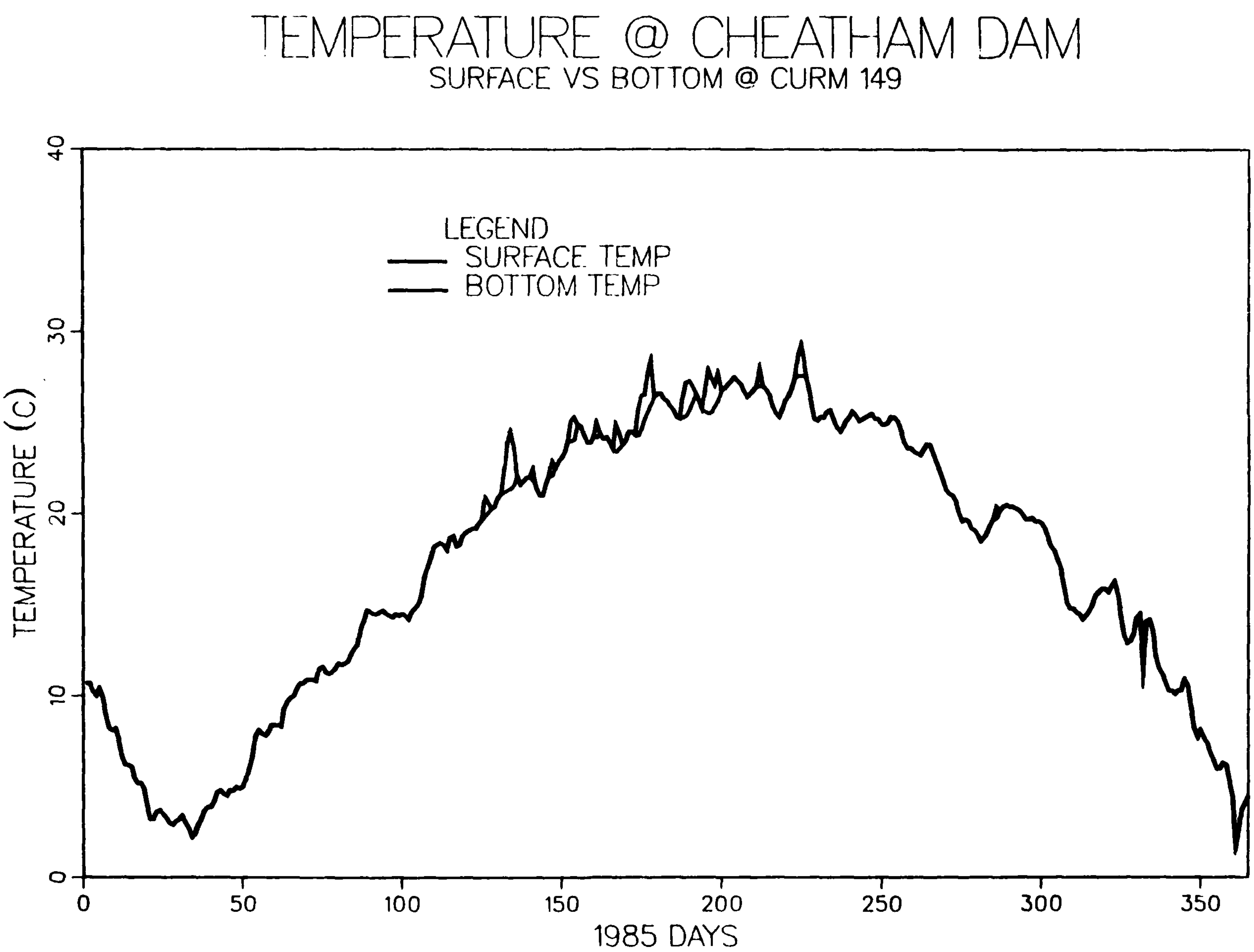
The long-term low flow periods of 1968 and 1969 resulted in the highest residence time periods with many values between 15 and 20 days. Long-term low flows in the latter part of 1980 and early 1981 also produced residence times in excess of 15 days. The low flows of 1984 produced a short period of high hydraulic residence times.

In summary, residence times in Cheatham Lake are generally between 2 and 7 days with longer storage times resulting from prolonged low-flow periods. Short-duration low flows of less than 3 days do not produce the kind of storage times likely to cause water quality problems. Reservoir stratification and attendant water quality problems are more likely when residence times exceed 10 days.

Reservoir Stratification Analysis

Cheatham Lake can be described as a run-of-the-river reservoir having only short periods of intermittent stratification. The model was used to describe stratification periods during 1985, 1986 and 1987. Since any stratification is most likely to occur in the pool closest to Cheatham Dam, time-series plots of predicted temperature at the surface and bottom are shown by Figures 12-14. Figure 12 shows that 12 short periods of stratification occurred in 1985, Figure 13 shows 6 periods for 1986 and Figure 14 shows one long period on two short ones for 1987.

FIGURE 12



TEMPERATURE @ CHEATHAM DAM
SURFACE VS BOTTOM @ CURM 149
LEGEND
SURFACE TEMP
BOTTOM TEMP
TEMPERATURE (C)
0
10
20
30
40
0
50
100
150
200
250
300
350
1985 DAYS

FIGURE 13

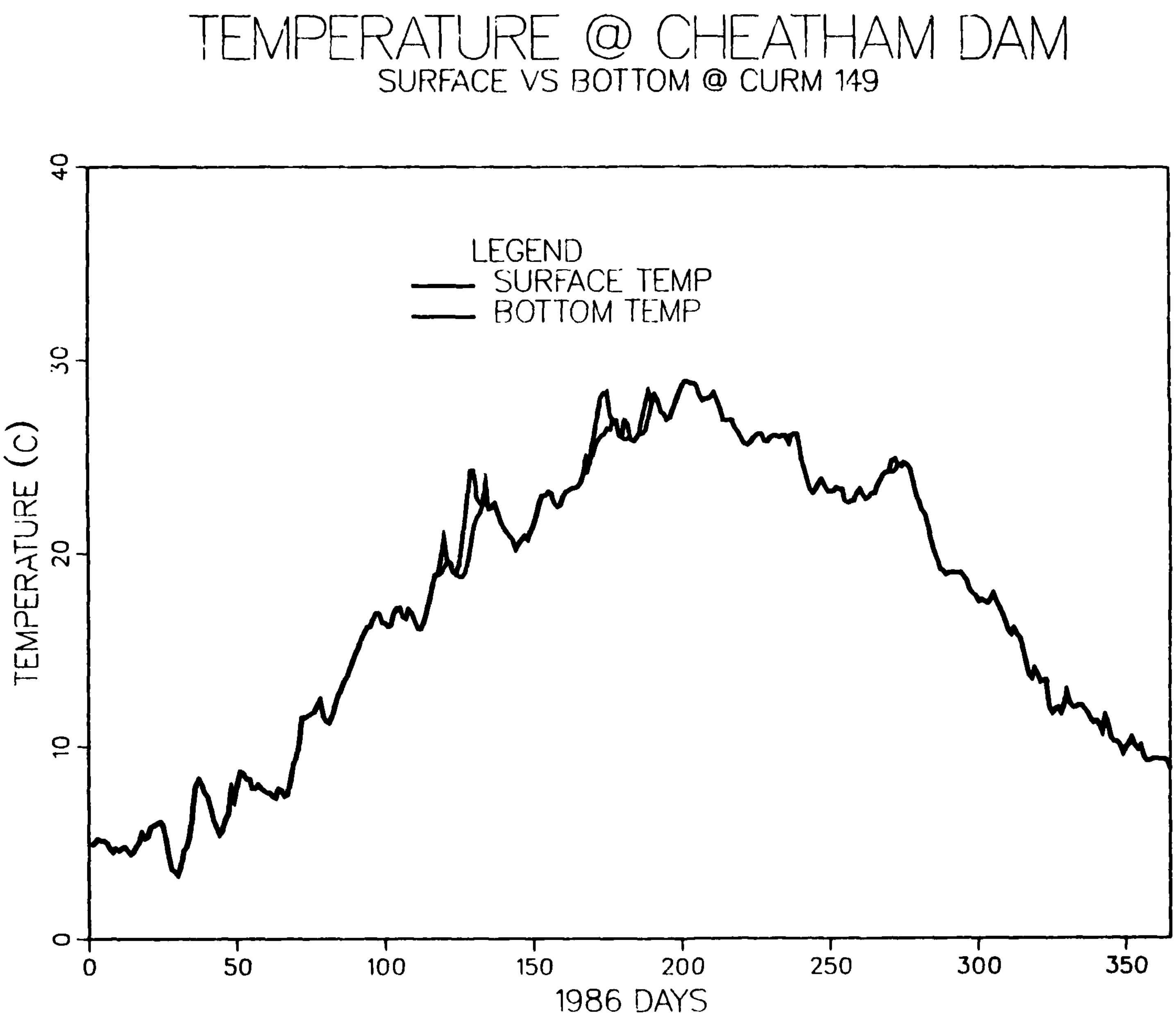
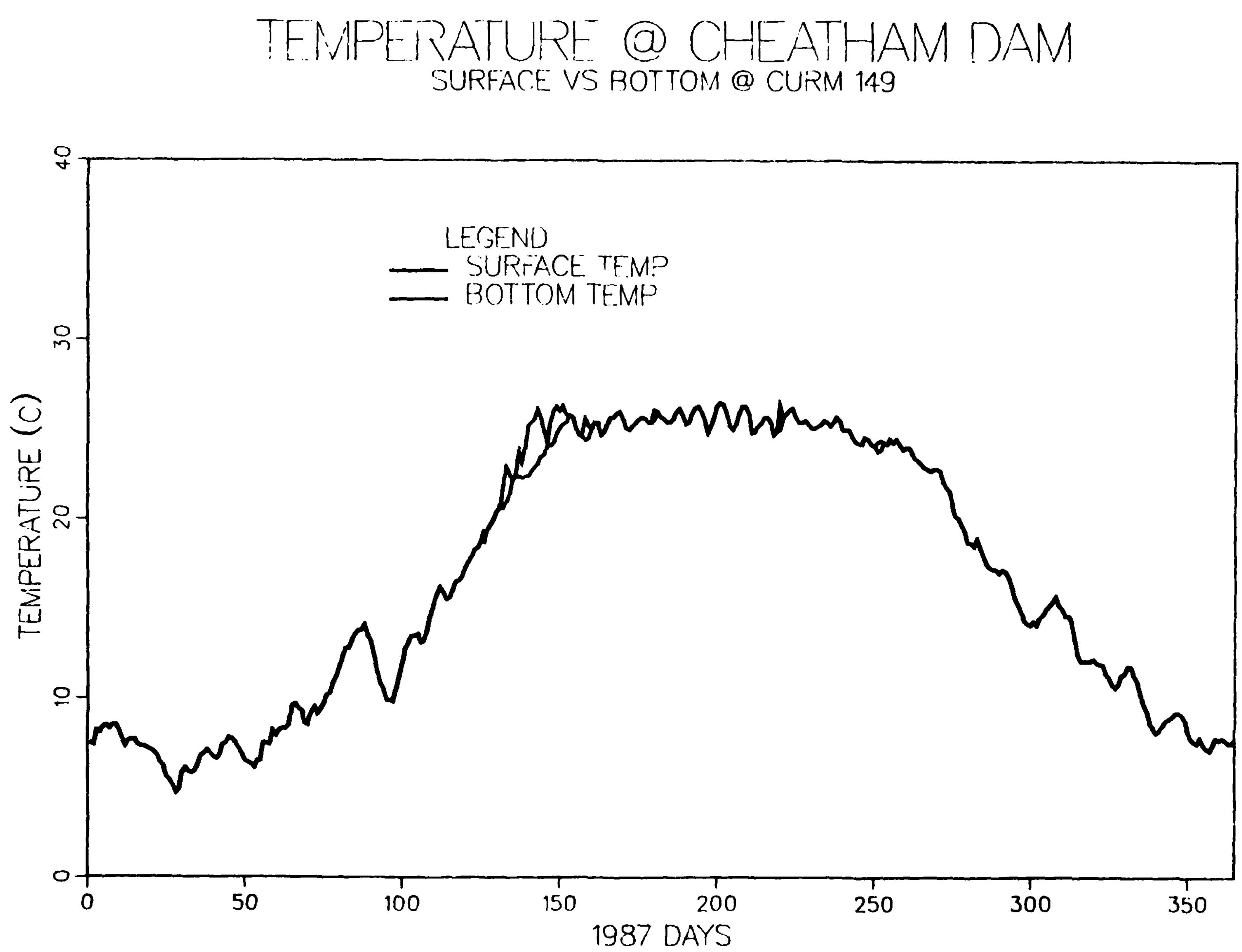

TEMPERATURE @ CHEATHAM DAM
SURFACE VS BOTTOM @ CURM 149
LEGEND
SURFACE TEMP
BOTTOM TEMP
TEMPERATURE (C)
0
10
20
30
40
0
50
100
150
200
250
300
350
1986 DAYS

FIGURE 14



TEMPERATURE @ CHEATHAM DAM
SURFACE VS BOTTOM @ CURM 149
LEGEND
SURFACE TEMP
BOTTOM TEMP
TEMPERATURE (C)
0
10
20
30
40
0
50
100
150
200
250
300
350
1987 DAYS

The number of degrees of top to bottom stratification can be measured from Figures 12-14. In 1985, top to bottom temperature differences were between 1 and 3.2° C; in 1986, differences were between 1 and 3.0°C. Obviously, Cheatham Lake does not regularly stratify and the intermittent stratification is not very pronounced. An analysis of flows related to stratification showed that releases of 6,000 cfs or less from Old Hickory would initiate thermal stratification while stronger stratification became evident at flows of 3000 cfs or less.

Longitudinal changes in surface temperature from Old Hickory to Cheatham dams were found to be slight as shown by Table 5. The changes are both heating and cooling according to seasons and most changes are less than 3° C. The plotting program CHTL.FOR was used for this analysis but the plots only confirm the information shown by Table 5.

In summary, temperature variations in Cheatham Lake were minor and indicated that the lake is usually mixed vertically and has retention times too short to develop longitudinal variations. At lower flows, slight stratification begins to develop, but this is quickly destroyed when flows increase.

Dissolved Oxygen Analysis

Dissolved oxygen is a water quality parameter of concern in Cheatham Lake. U.S.G.S. monitoring data show that the DO in Old Hickory release is often below 5 mg/l (See Figures 6, 7 and 8). The Nashville Metro river run data show that DO values remain low at Clees Ferry, but are perhaps one mg/l higher there than at the Old Hickory Dam (See Figures 9, 10 and 11). Both point and non-point sources of wastewater exist

Table 5

Longitudinal Temperatures Predicted
for Cheatham Lake

		Temperature at Surface °C			
Year	J Day	150.5	165.5	180.5	213.5
1985	149	22.9	22.8	22.9	21.5
	205	27.3	26.6	26.2	26.2
	226	28.2	27.9	26.4	24.4
	234	25.7	25.3	24.8	25.0
	261	23.3	22.8	23.5	22.3
	289	20.5	20.4	20.0	20.0
1986	141	21.1	20.8	20.0	20.0
	162	23.3	23.4	23.1	23.1
	183	25.9	25.5	25.5	24.0
	197	27.4	27.4	27.3	27.3
	220	26.0	25.4	25.3	25.1
	239	26.2	25.5	25.2	24.2
	260	23.3	23.3	22.9	23.1
	281	22.2	21.8	20.9	21.7
1987	147	24.3	24.7	23.7	23.4
	168	25.8	25.7	25.0	23.3
	196	25.3	24.4	24.0	24.1
	217	25.3	24.2	23.3	23.1
	245	23.9	23.8	24.1	23.2
	259	23.7	23.5	23.3	23.9
	280	18.0	18.6	19.7	18.2
	308	15.6	15.8	15.8	16.0
	322	11.7	12.2	12.3	12.7

along the upper reaches of Cheatham Lake which are of concern to regulatory agencies.

Figures 9, 10, and 11 and Table 3 show that BETTER is a capable predictor of DO between Old Hickory and Clees Ferry. Some Corps data were used to calibrate the temperature and DO portions of the model downstream of Clees Ferry for 1985 and to validate model results for 1986-87. Thus, it is reasonable to use BETTER to assess the DO situation in Cheatham Lake.

The U.S.G.S. monitor at Old Hickory Dam showed DO levels below 5 mg/l for several summer days during 1985 and 1986 and the Metro river run data tended to confirm these measurements. During 1987, only two days were below 5 mg/l. Between Old Hickory Dam and the Nashville Central Wastewater Treatment Plant, some reaeration occurs and it is unusual for the reservoir DO values to be below 5 mg/l although the values range from 5 to 6 mg/l for a long period (See Figures 6, 7 and 8).

Little, if any, change in DO occurs between the Central WWTP discharge and Clees Ferry so that the Clees Ferry DO values border on 5 mg/l for the summer period. (See Figures 9, 10 and 11). Very little change in DO is evident between Clees Ferry and Cheatham Dam as shown by Figures 15-17. DO values at Cheatham Dam were between 5 and 6 mg/l for portions of the summers of all these modeled years. During periods of intermittent stratification, the bottom DO values are between two and four mg/l lower than surface values. This is caused by benthic and water-based demands in the lower depths and photosynthesis and reaeration at the surface.

FIGURE 15

DISSOLVED OXYGEN @ CHEATHAM DAM
SURFACE VS BOTTOM @ CURM 149

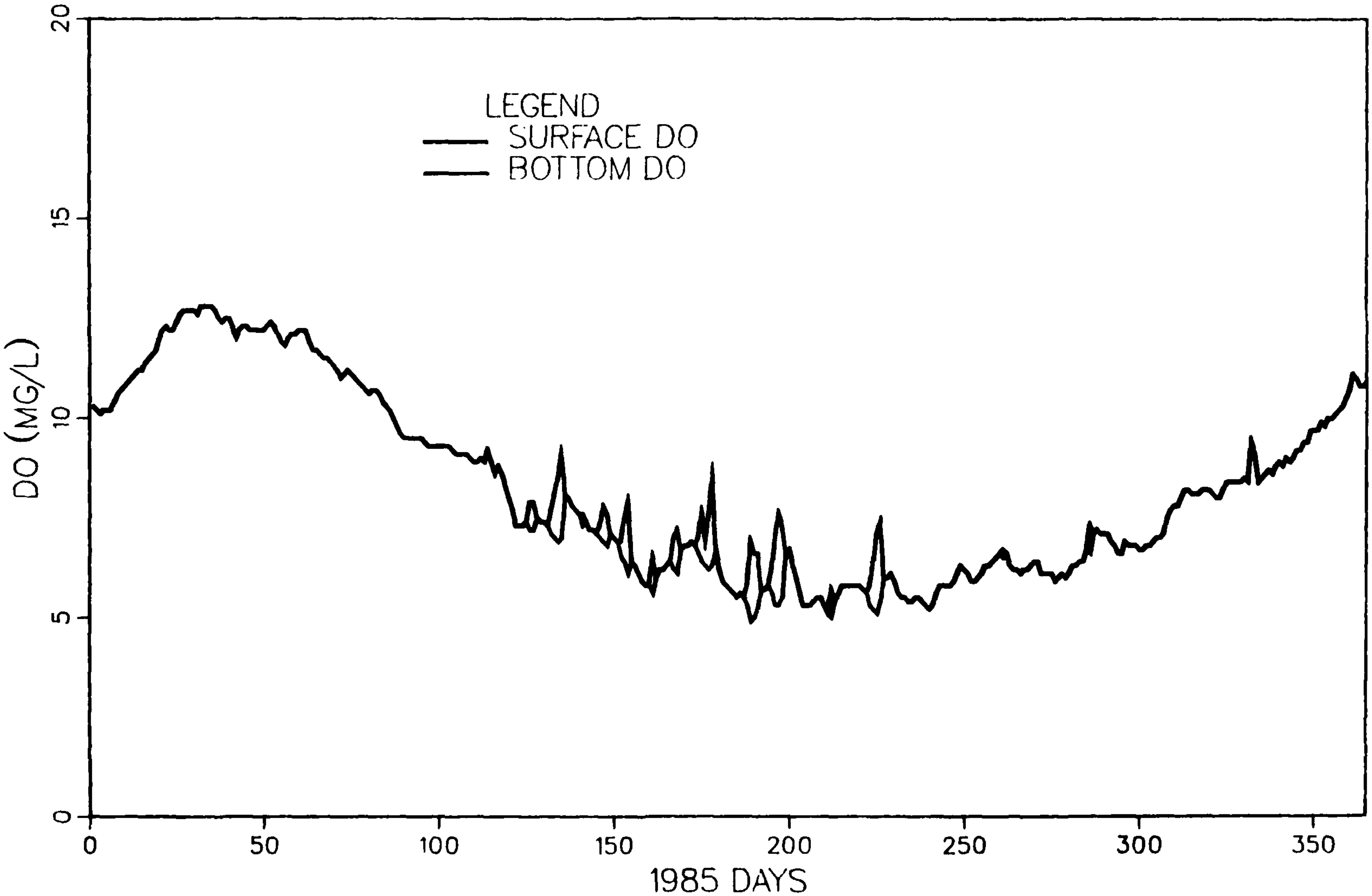


FIGURE 16

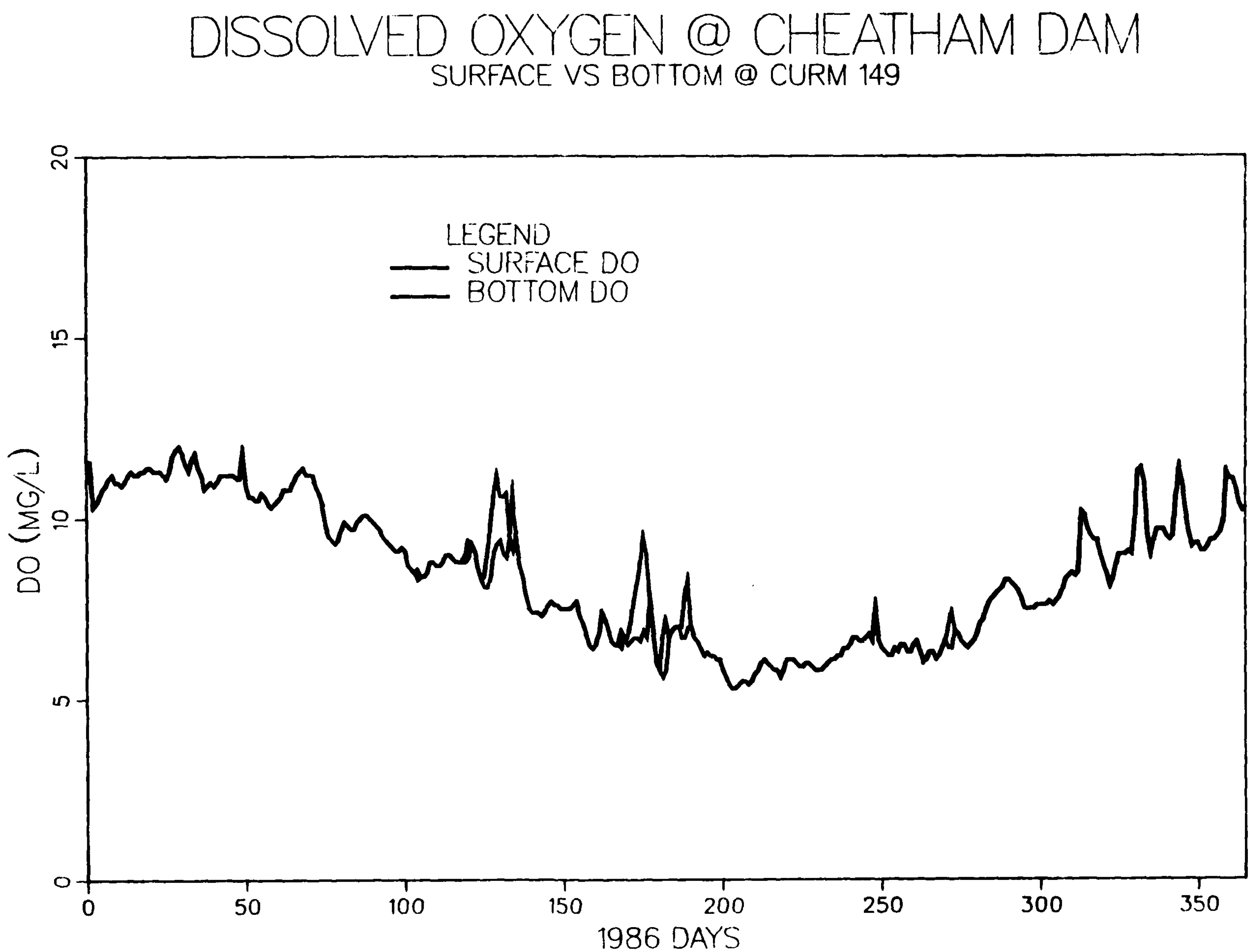
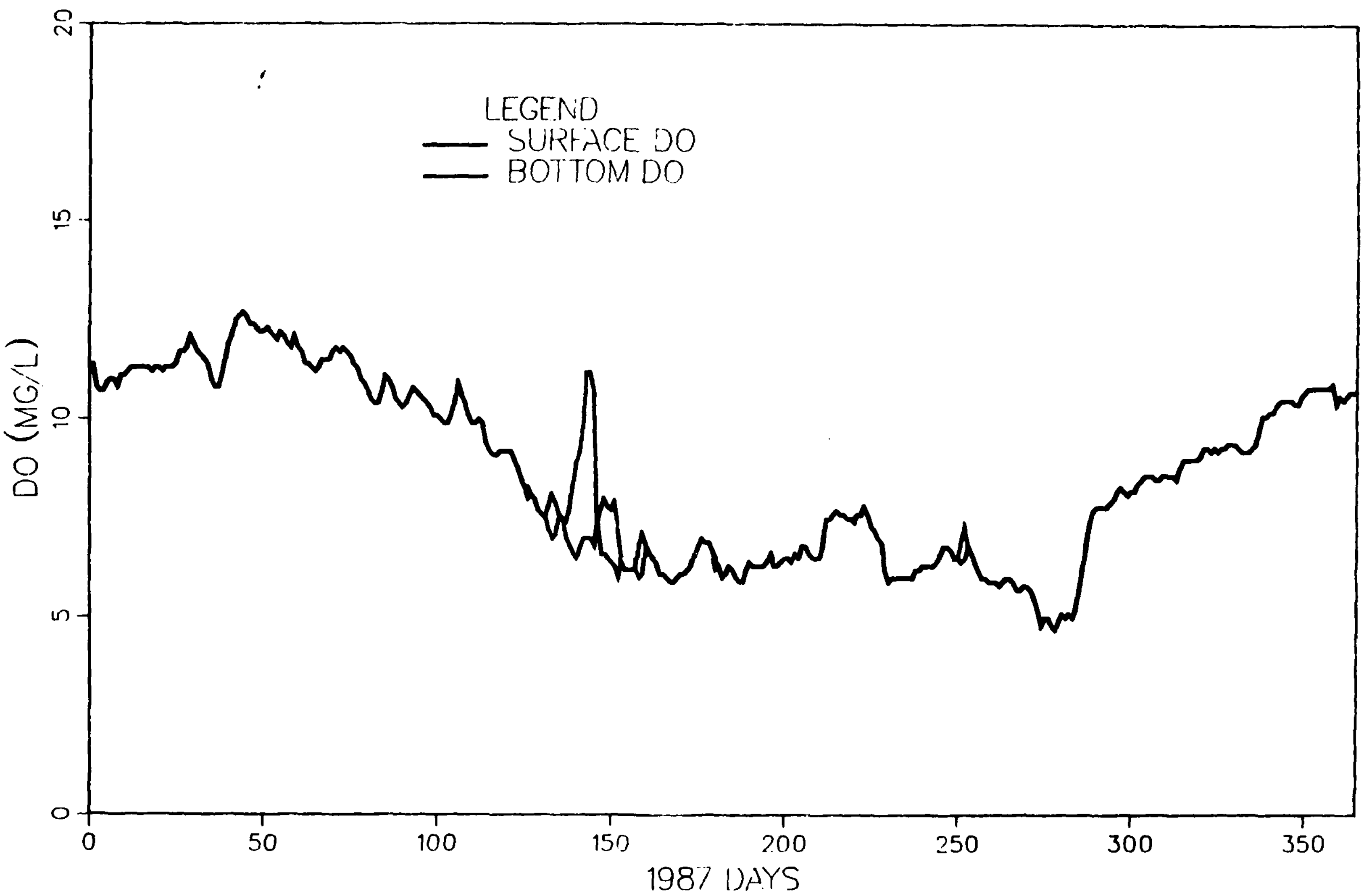

DISSOLVED OXYGEN @ CHEATHAM DAM
SURFACE VS BOTTOM @ CURM 149
LEGEND
SURFACE DO
BOTTOM DO
DO (MG/L)
0
5
10
15
20
0
50
100
150
200
250
300
350
1986 DAYS

FIGURE 17

DISSOLVED OXYGEN @ CHEATHAM DAM

SURFACE VS BOTTOM @ CURM 149



Plots prepared by CHTL.FOR and CHTD.FOR confirmed the DO dynamics described earlier. Therefore, special plots were prepared two days each during the summers of 1985, 1986, and 1987 to show the DO concentration in the surface cells from Old Hickory to Cheatham. The six days selected were all in August and coincided with Metro river run data. The plots are, in essence, "DO sag" curves and are shown by Figures 18-23. In studying these plots , several points should be noted. First, the model starts with DO values from the U.S.G.S. monitor which are not always in agreement with Metro river run data. Second, if the model starts with low DO, it will improve concentrations by reaeration. Third, the model DO values are daily average DO's while the river run DO values are collected at an instant during daylight hours.

Figure 18 shows a low DO release which improved less than one mg/l through the reservoir. The river run data are about 1 mg/l higher. Figure 19 shows a steady value of DO with river run data in close agreement. Figure 20 has a constant DO in fair agreement with river run data. Figure 21 shows a slight improvement in DO with river run data being about 1 mg/l high and looking unusual. Figure 22 shows a dropping DO with reservoir length and river run data following the same trend but about 0.5 mg/l lower. Figure 23 also shows a dropping DO pattern with river run data being stable.

None of the DO data nor the BETTER predictions show a DO sag below Nashville for 1985, 1986 or 1987. Low DO levels in the Old Hickory releases see little change while passing through the reservoir. This is unusual and is probably the result of several interrelated factors.

FIGURE 18

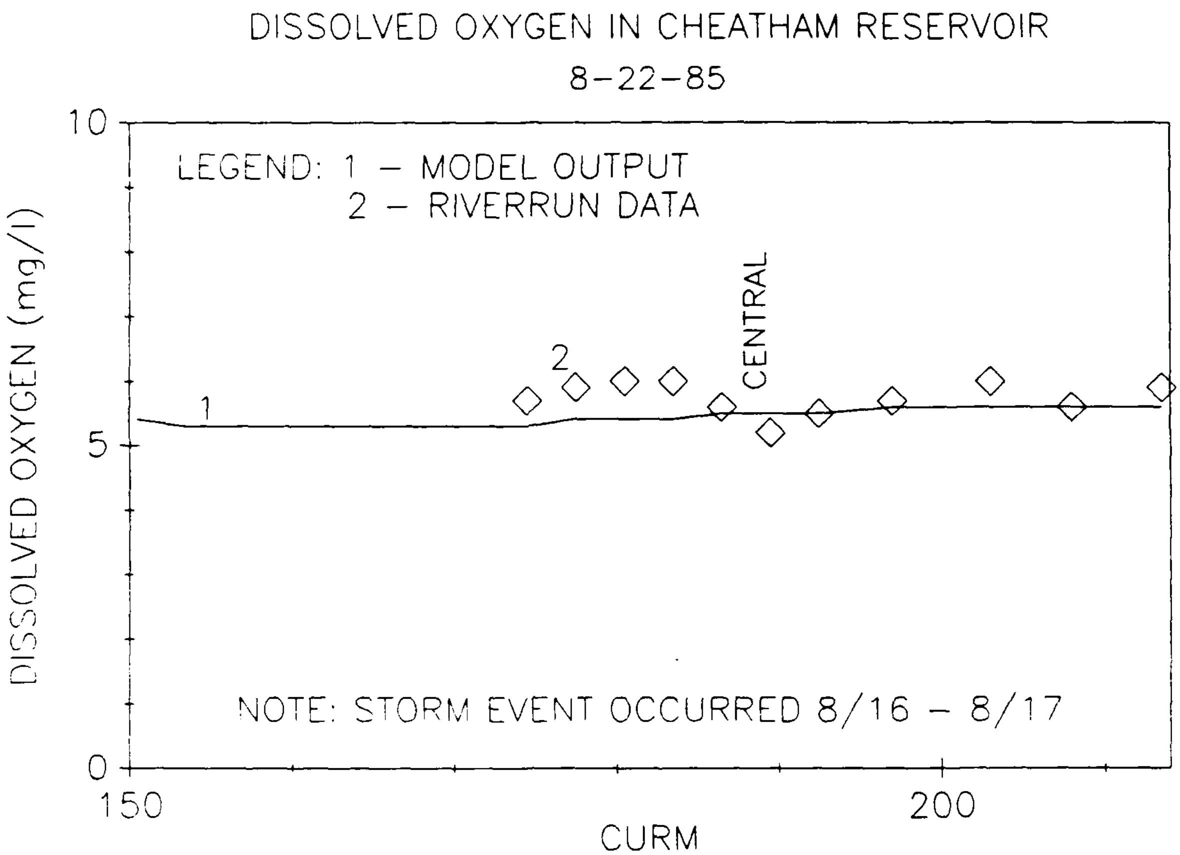


FIGURE 19

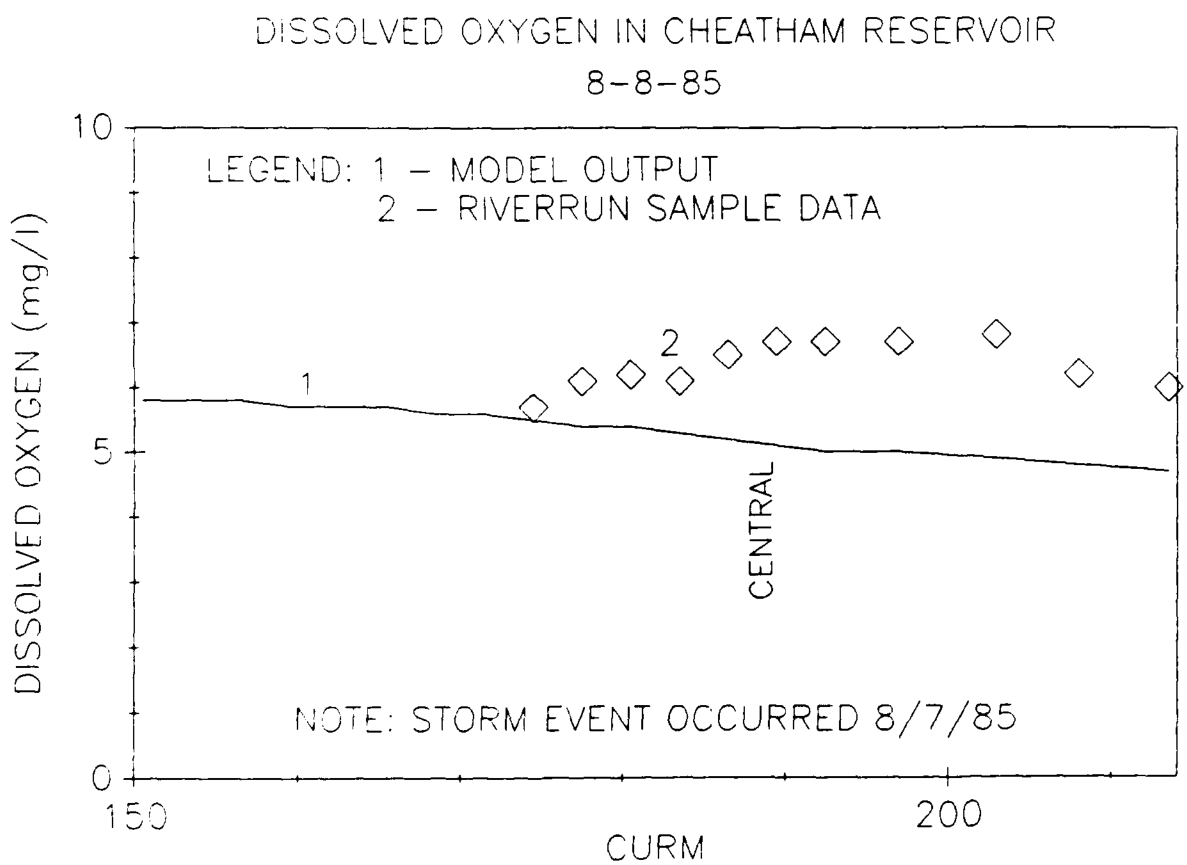


FIGURE 20

DISSOLVED OXYGEN IN CHEATHAM RESERVOIR

8-13-86

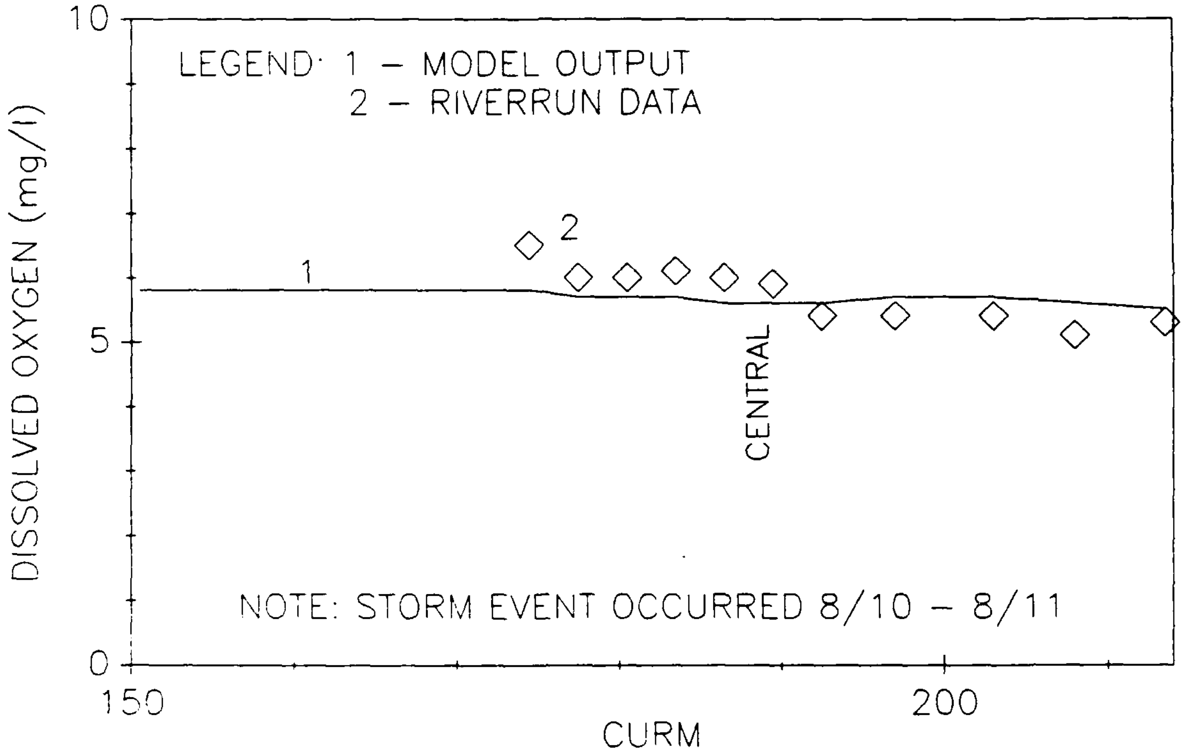


FIGURE 21

DISSOLVED OXYGEN IN CHEATHAM RESERVOIR

8-20-86

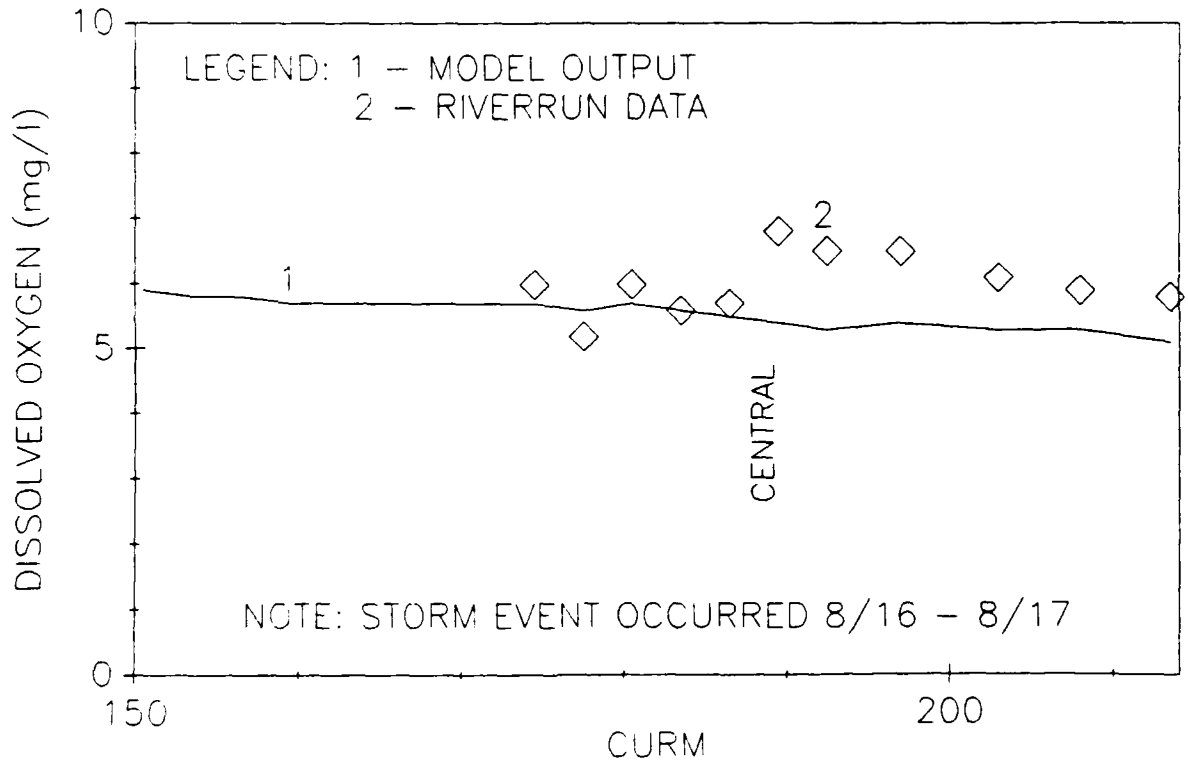


FIGURE 22

DISSOLVED OXYGEN IN CHEATHAM RESERVOIR

8-5-87

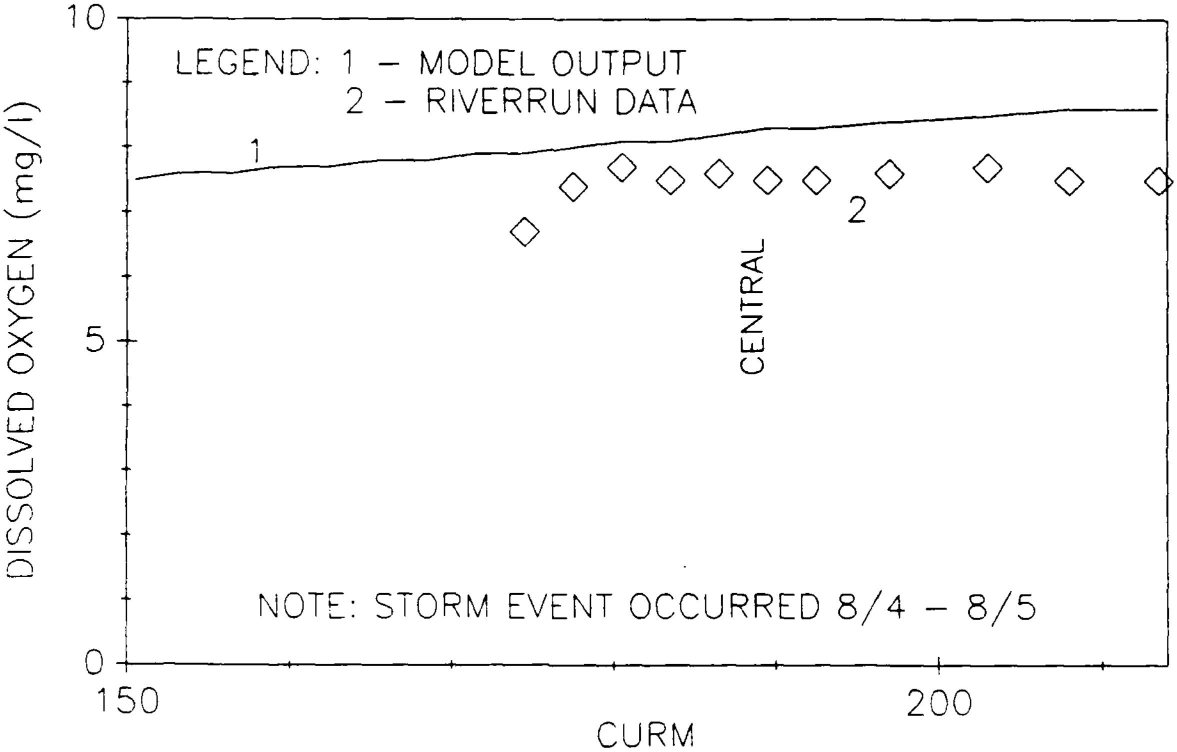
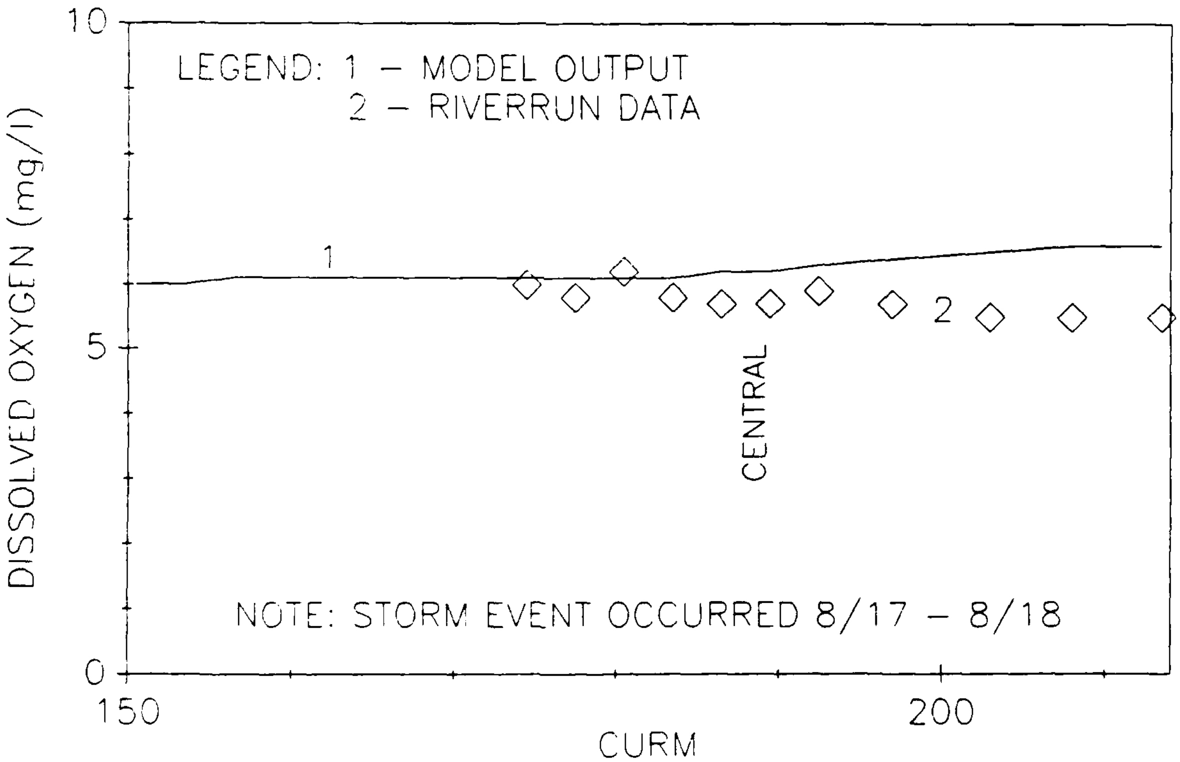


FIGURE 23

DISSOLVED OXYGEN IN CHEATHAM RESERVOIR

8-20-87



An interesting use of BETTER would be to determine the effect of aeration, point sources, non-point sources, photosynthesis and benthic demand on the DO levels of Cheatham Lake.

Manganese from J. Percy Priest Releases

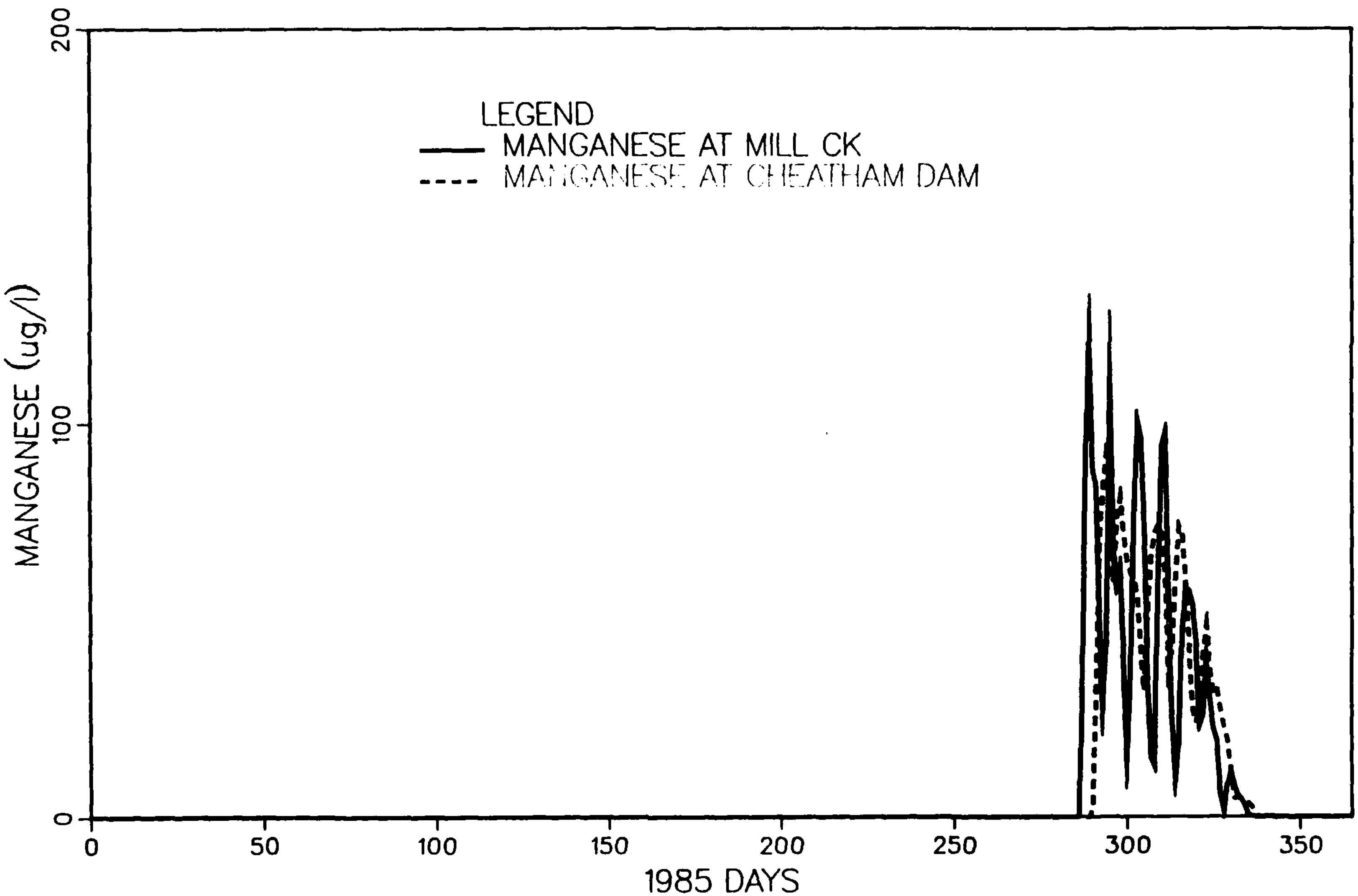
Manganese concentrations in the releases from J. Percy Priest Reservoir for 1985 were simulated with the DYE variable using a decay rate to simulate the oxidation of manganese. The initial condition for DYE in Cheatham Lake and its inflows was set equal to zero. The DYE values for the Stones River inflow were increased from 0.0 on May 1 to a maximum of 1000 μg/l on September 30 and decreased back to 0.0 by the end of November. This pattern corresponds to the anaerobic buildup of dissolved manganese in the hypolimnion and the mixing and oxidation of the manganese during fall turnover. (Corps, 1978).

The DYE decay rate was set at 0.75 day-1 to correspond with reported field study manganese oxidation rates (Chen, 1984). Values range from 0.85 to 1.70 day^{-1} (base e). For the BETTER model implementation these decay rates must be converted to the fraction remaining at the end of a day ($DYEDK=1-e^{-k}$) giving a model coefficient range of 0.57 to 0.82.

Figure 24 shows the pattern of manganese at two stations downstream of the Stones River during the Fall of 1985. Peak concentrations near Mill Creek ranged from 70 to 170 ug/l, while those at Cheatham Dam were lower because of dilution and oxidation during reservoir passage. Concentrations were zero until the middle of October when releases from J. Percy Priest Reservoir began.

FIGURE 24

MANGANESE IN CHEATHAM LAKE
(BASED ON J. PERCY PRIEST RELEASE)



The type of simulation used for manganese may be used for modeling other metals or for tracking chemical spills at any point within the reservoir.

Sewered Population Increase Simulations

The BETTER model was used to study the effect of an increase in population in Metropolitan Nashville on Cheatham Lake. This was accomplished by increasing the sewage treatment plant effluent loading by a factor of two. The parameters involved were suspended solids, dissolved organic matter, detritus, ammonia, nitrate and phosphate.

To run the model, the input file generate program (GCHIN85.FOR) was modified to multiply each parameter concentration for each inflow location (e.g., Central Plant is inflow no. 5). After executing the generate program, the model was run for the year (1985).

The CHBETR.FOR program was edited to provide for plotable output that was used to compare normal discharges with increased sewage discharge. Output was sent to file COMPLT85.OUT, and was used to produce plots that compared base run values to the population simulation values for each parameter at Clees Ferry (Cell 9,1).

Techplot was used to produce multiple plots showing the comparison between base run and increased population conditions at Clees Ferry, which is downstream of the three largest sewage treatment plants on the reservoir. These plots showed only slight increases in DO, BOD, NH3, SS and PO4 due to a doubling in population. Figure 25 for BOD and Figure 26 for DO are typical results with the top line being background and the bottom line for simulation results for BOD while the DO lines are reversed as DO is slightly lower for the population increase.

Figure 25

BOD COMPARISON FOR POPULATION STUDY

CHEATHAM RESERVOIR
@ CLEES FERRY

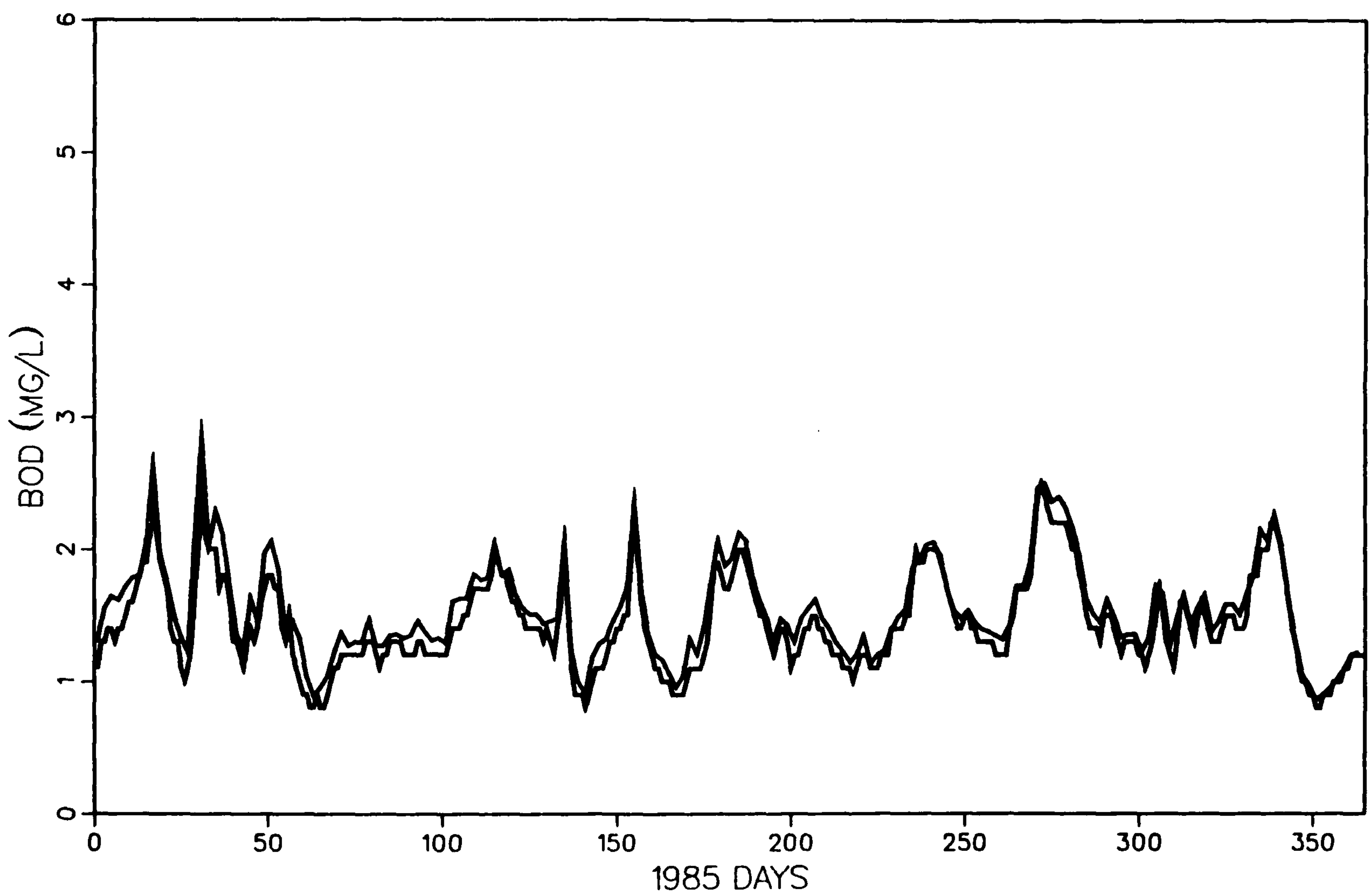
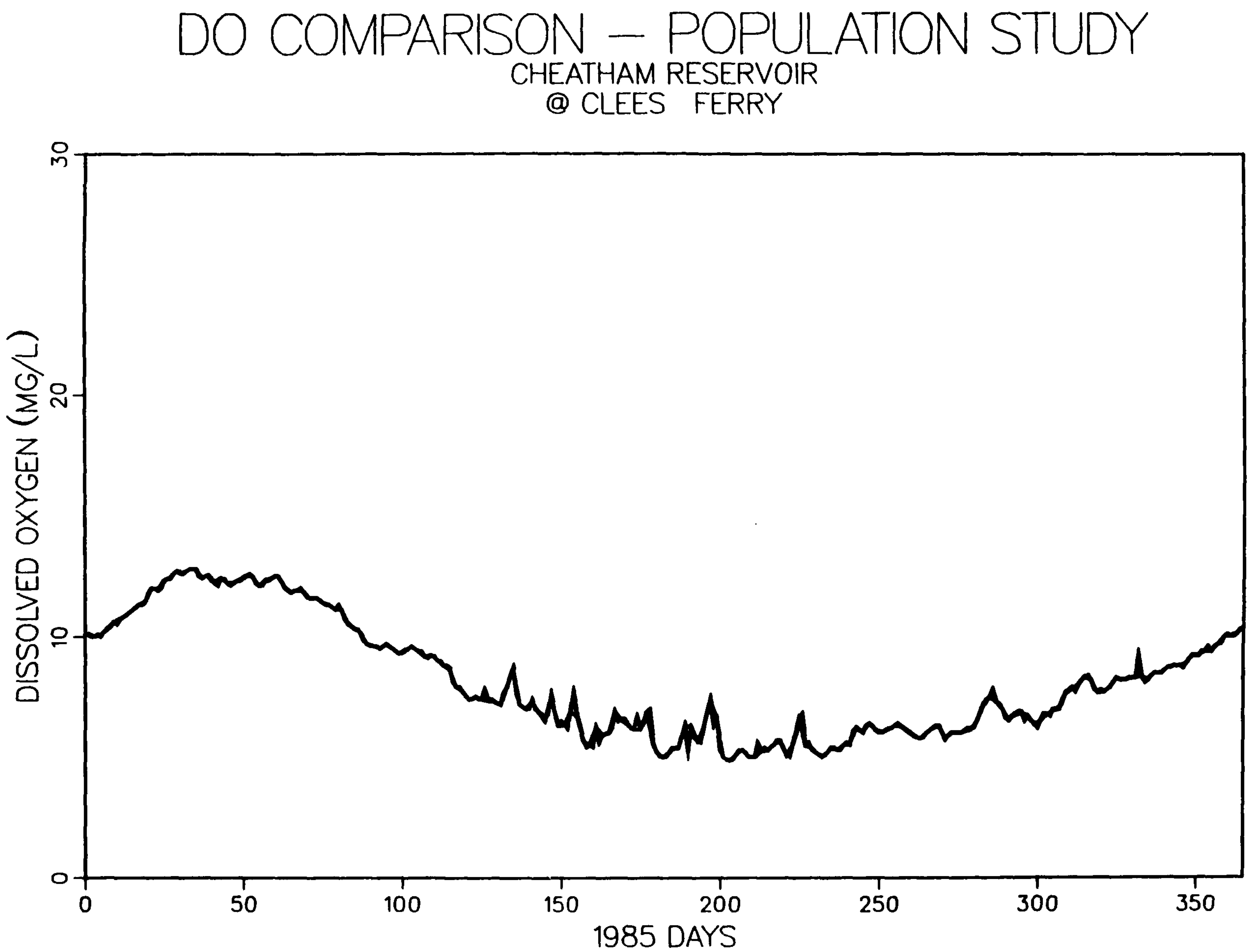


Figure 26


DO COMPARISON — POPULATION STUDY
CHEATHAM RESERVOIR
@ CLEES FERRY
DISSOLVED OXYGEN (MG/L)
0
10
20
30
0
50
100
150
200
250
300
350
1985 DAYS

A similar study could be made to determine the effect of discharging raw or primary sewage effluent into the reservoir. Coliform bacteria could be modeled in the same manner. Thus the model is quite versital in handling such scenarios.

A Mill Creek Storm Water Runoff Event

A storm event was simulated for Cheatham Lake using the BETTER model to determine the effects of urban runoff, represented by Mill Creek, on reservoir water quality for the 1985 model year.

A low flow period was selected by reviewing Old Hickory releases for 1985. The time period selected was September 16 through September 18. The average Old Hickory flow for this period was 4360 cfs.

Mill Creek flows were based on a 1 inch rainfall runoff event, which corresponded to 15 cfs per square mile for the first day, 8 for the second day and 4 cfs for day 3 of the simulation. The Mill Creek drainage area is 108 square miles. Flows for the model run were 1620, 864, and 432 cfs for the three days, respectively. The changes in flow and water quality data were made in the inflow file (CHIN85.DAT).

Outflows from Old Hickory Dam were reduced by the amount of flow added to Mill Creek to maintain the water budget.

Water quality inputs were changed to reflect representative urban storm runoff conditions. Suspended solids were input at 160 mg/l, about 8 times the normal condition. DOR and detritus were increased to 8 mg/l, representing a BOD of 16 mg/l. Ammonia and phosphorus values were already in line with the guidelines established for runoff quality. Quality parameters were obtained from Milligan, et al. (1984) and Overton and Meadows (1976).

The model was run for the entire year, with time-series graphs used to detect any changes between normal conditions and the storm event. The simulated storm event had almost no impact on Cheatham Lake water quality except for suspended solids which increased almost 3-fold. Figures 27-29 are included for this simulation where the bottom line is the original condition.

SUMMARY AND CONCLUSIONS

The BETTER Model has been developed to simulate water quality in Cheatham Lake. The model is very good for temperature and dissolved oxygen simulations and fair for other parameters. Its running time of about 15 minutes of CPU time for an annual simulation is reasonable and makes multiple runs affordable.

Cheatham Lake is a short-residence time reservoir which seldom stratifies. Its biggest water quality problem is D.O. during the summer months when Old Hickory releases have low D.O. concentrations. Generally, the D.O. in Cheatham Lake remains relatively constant between Old Hickory and Cheatham Dams. A reasonable use of the model would be to evaluate the sources and sinks of D.O. as water passes through the Cheatham pool.

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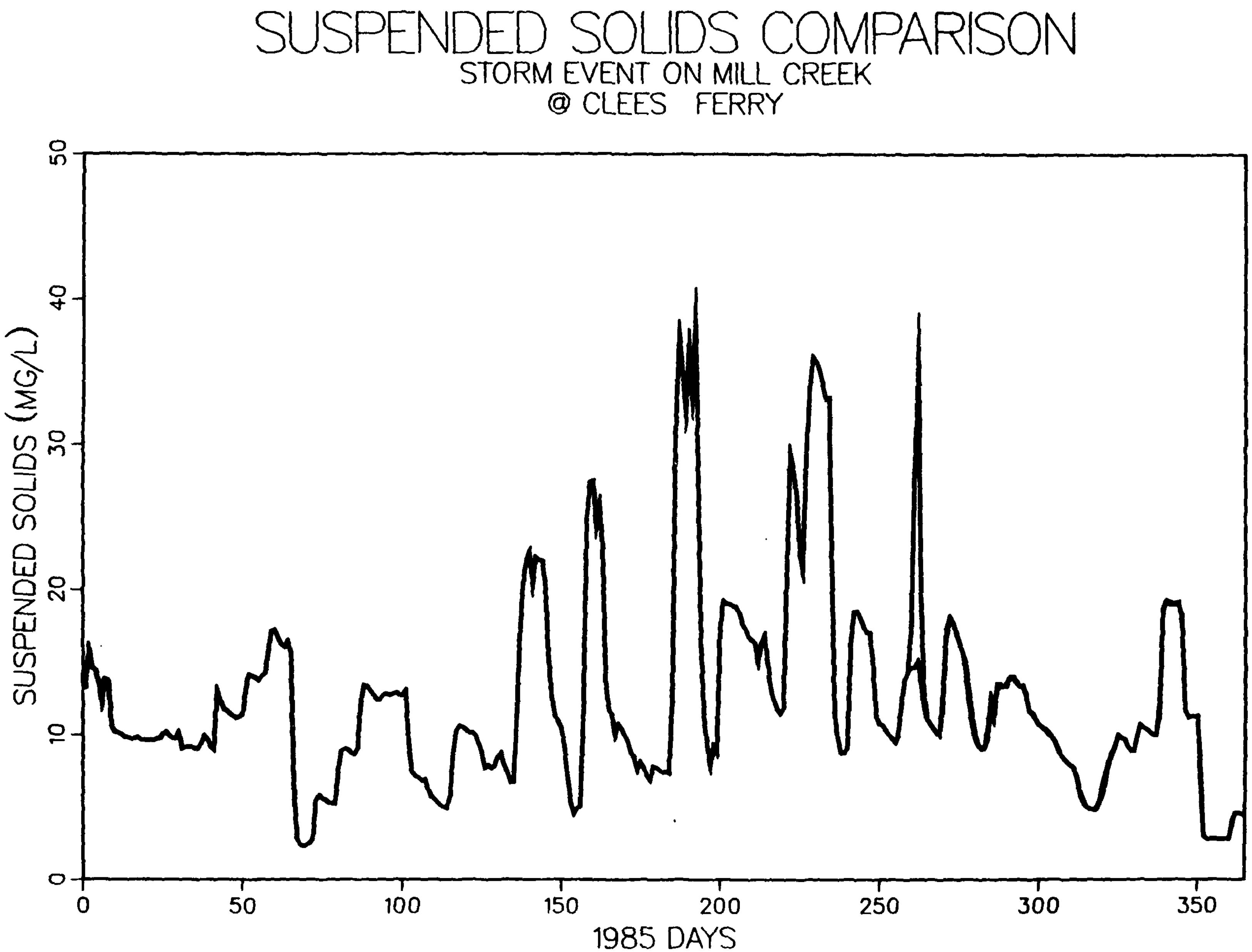
Overton, D.E. and Meadows, ME. (1976) Stormwater Modeling, Academic Press, New York.

Figure 27



SUSPENDED SOLIDS COMPARISON
STORM EVENT ON MILL CREEK
@ CLEES FERRY
SUSPENDED SOLIDS (MG/L)
0
10
20
30
40
50
0
50
100
150
200
250
300
350
1985 DAYS

Figure 28

DISSOLVED OXYGEN COMPARISON

STORM EVENT ON MILL CREEK
@ CLEES FERRY

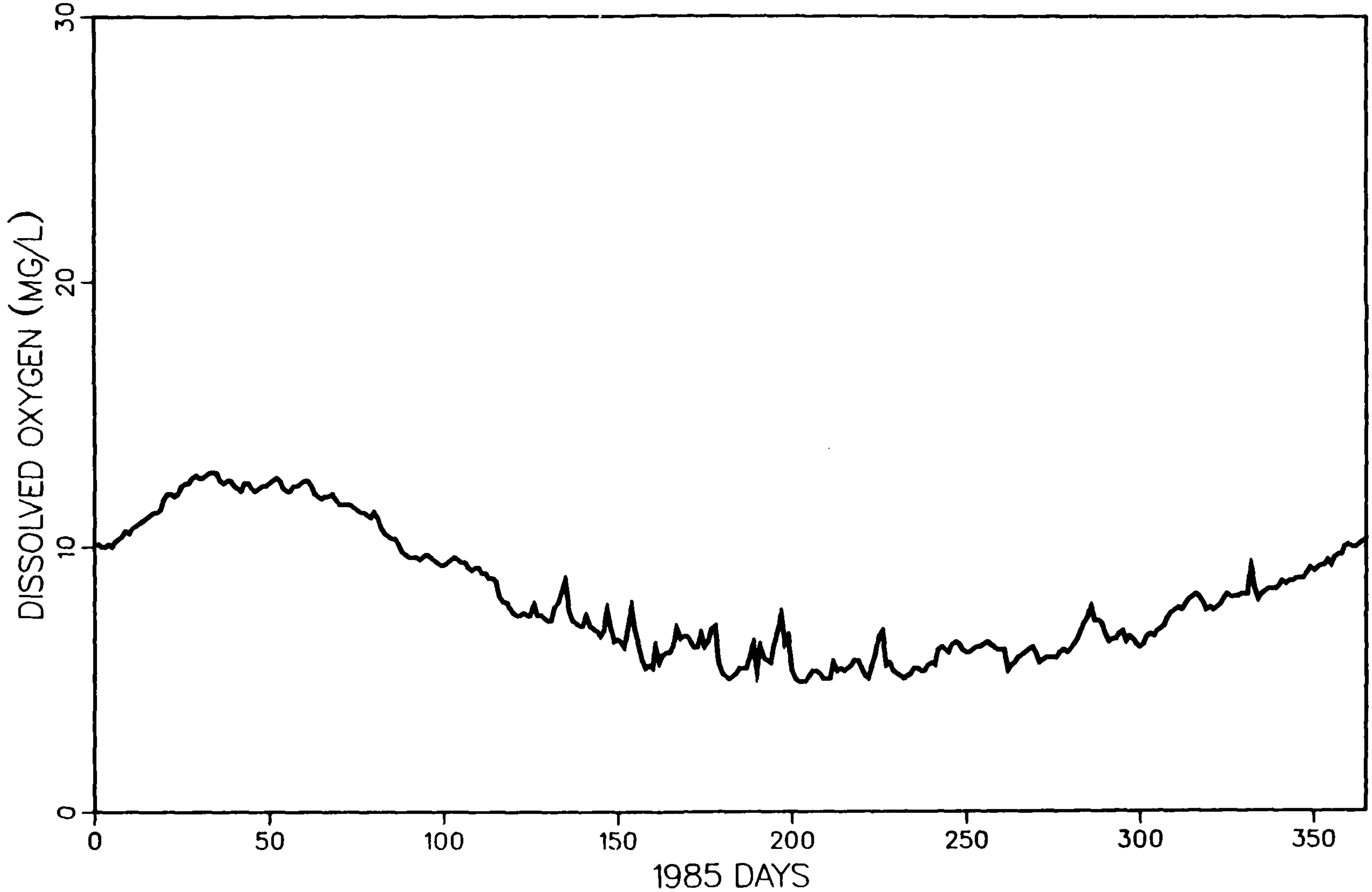
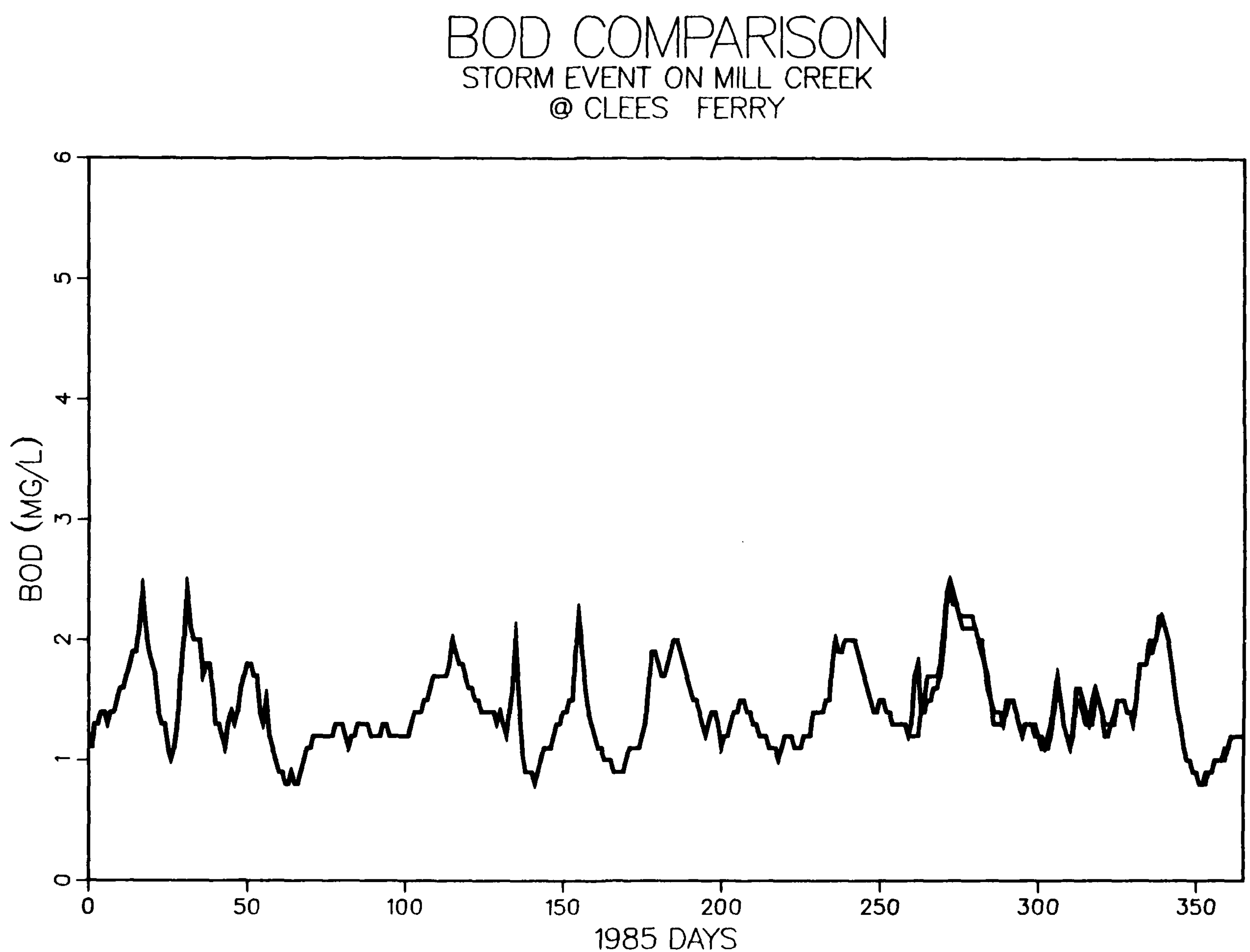


Figure 29


BOD COMPARISON
STORM EVENT ON MILL CREEK
@ CLEES FERRY
BOD (MG/L)
0
1
2
3
4
5
6
0
50
100
150
200
250
300
350
1985 DAYS

APPENDIX I

A Series of Time-Series Plots Showing the Model Output from BETTER and the Nashville Metro River Run Sampling Data

Figure AI 1-3. These figures show how the temperatures taken from the water quality monitor compared to temperatures taken by the Metro river runs just below Old Hickory Dam. Correlation is good, but the river run values are slightly lower. The fit was better during the later part of 1987. The means for 1985 and 1986 were statistically different, but by less than 1°C. The means for 1987 were the same, statistically.

Year	Difference in Means	Prob > T
1985	0.755 °C	0.0001
1986	0.832	0.0001
1987	0.160	0.329

Figure AI-1

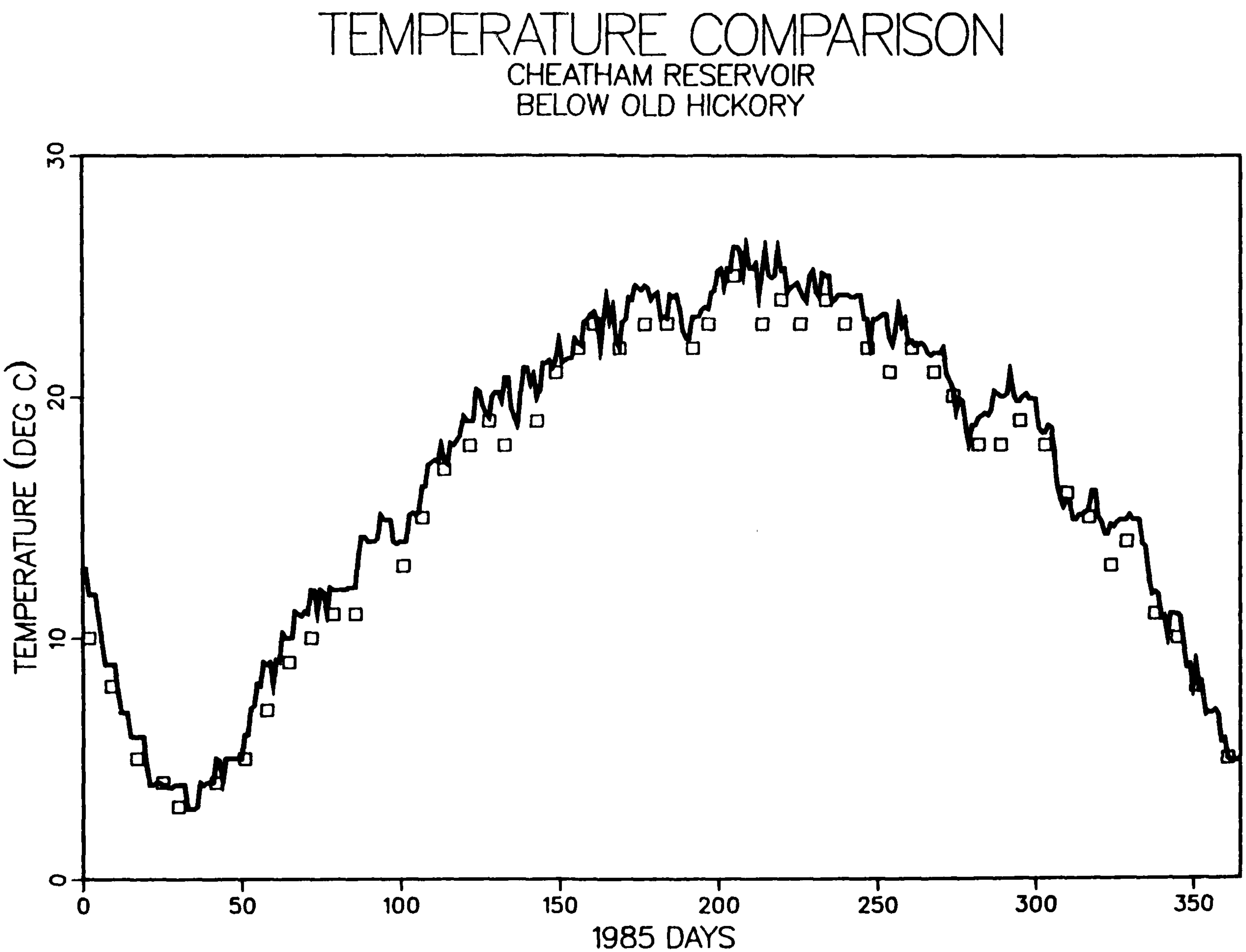

TEMPERATURE COMPARISON
CHEATHAM RESERVOIR
BELOW OLD HICKORY
TEMPERATURE (DEG C)
0
10
20
30
0
50
100
150
200
250
300
350
1985 DAYS

Figure AI-2

TEMPERATURE COMPARISON
CHEATHAM RESERVOIR
BELOW OLD HICKORY

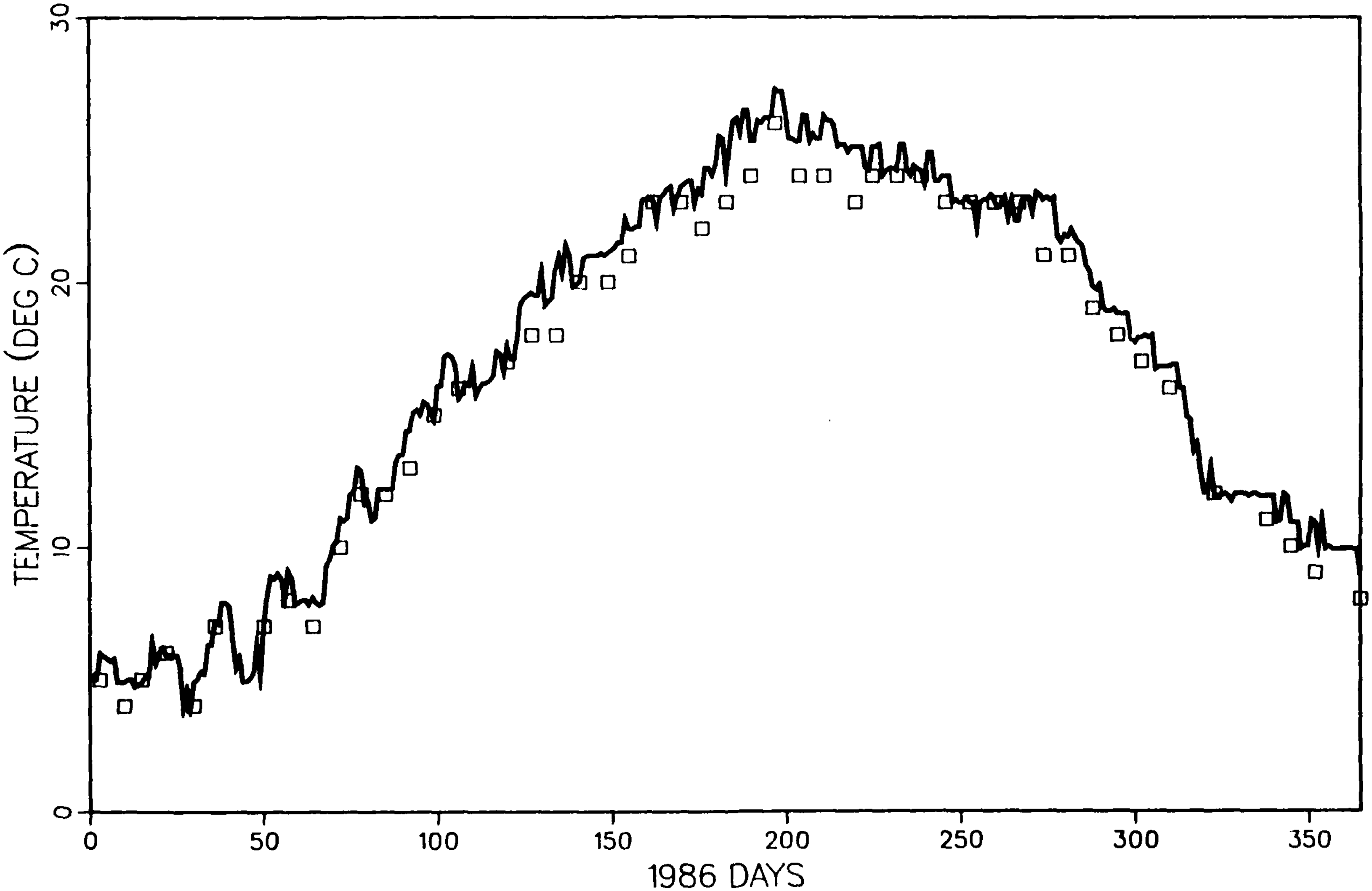
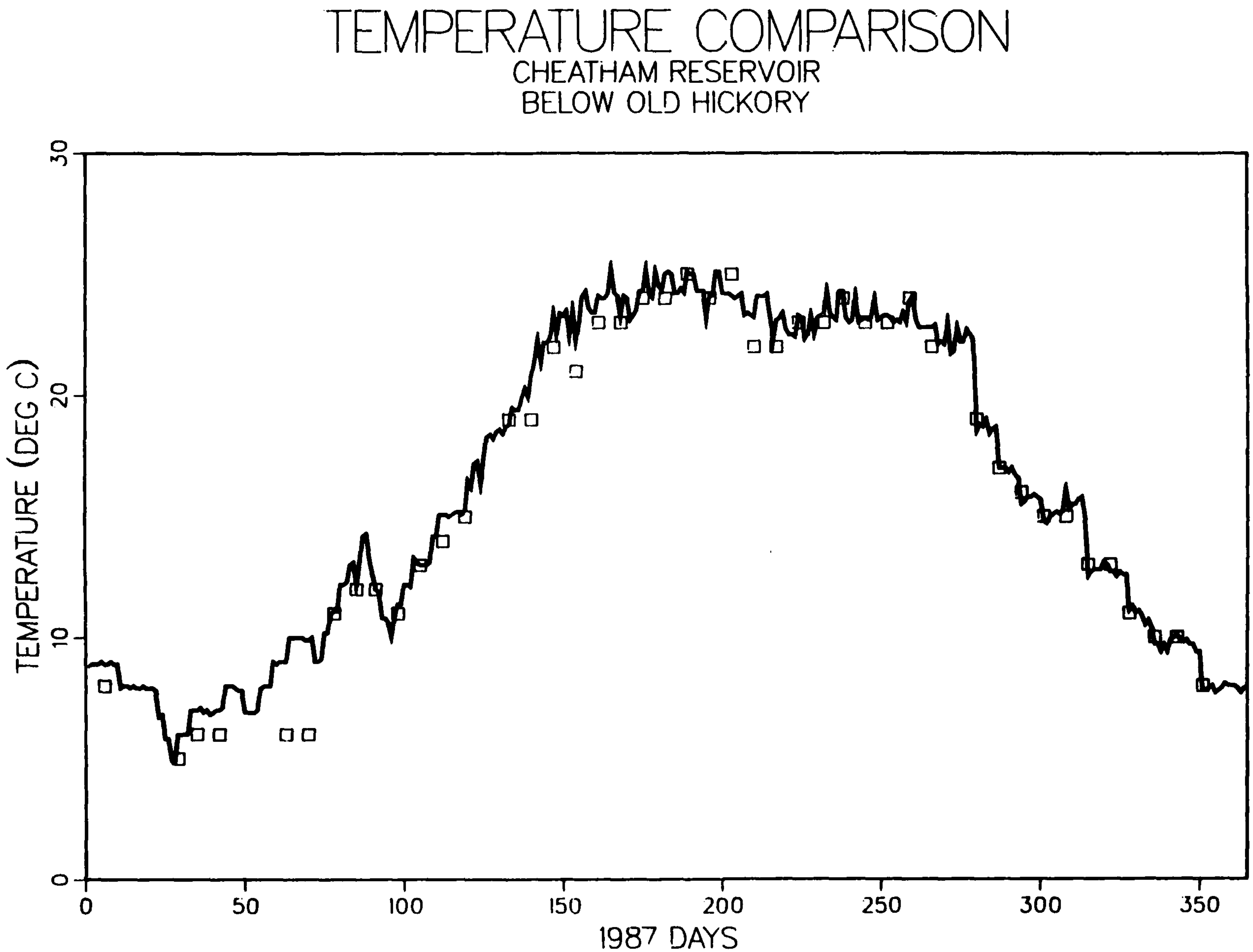


Figure AI-3


TEMPERATURE COMPARISON
CHEATHAM RESERVOIR
BELOW OLD HICKORY
TEMPERATURE (DEG C)
0
10
20
30
0
50
100
150
200
250
300
350
1987 DAYS

Figures AI 4-6. These figures show how the temperatures predicted by BETTER compared with Metro river run data at Clees Ferry. Again, correlation is good but the measured temperatures are usually lower than the predicted values. The means were statistically different but by less than 1°C.

Year	Difference in Means	Prob > T
1985	0.950 °C	0.0001
1986	0.806	0.0001
1987	0.502	0.0005

Figure AI-4

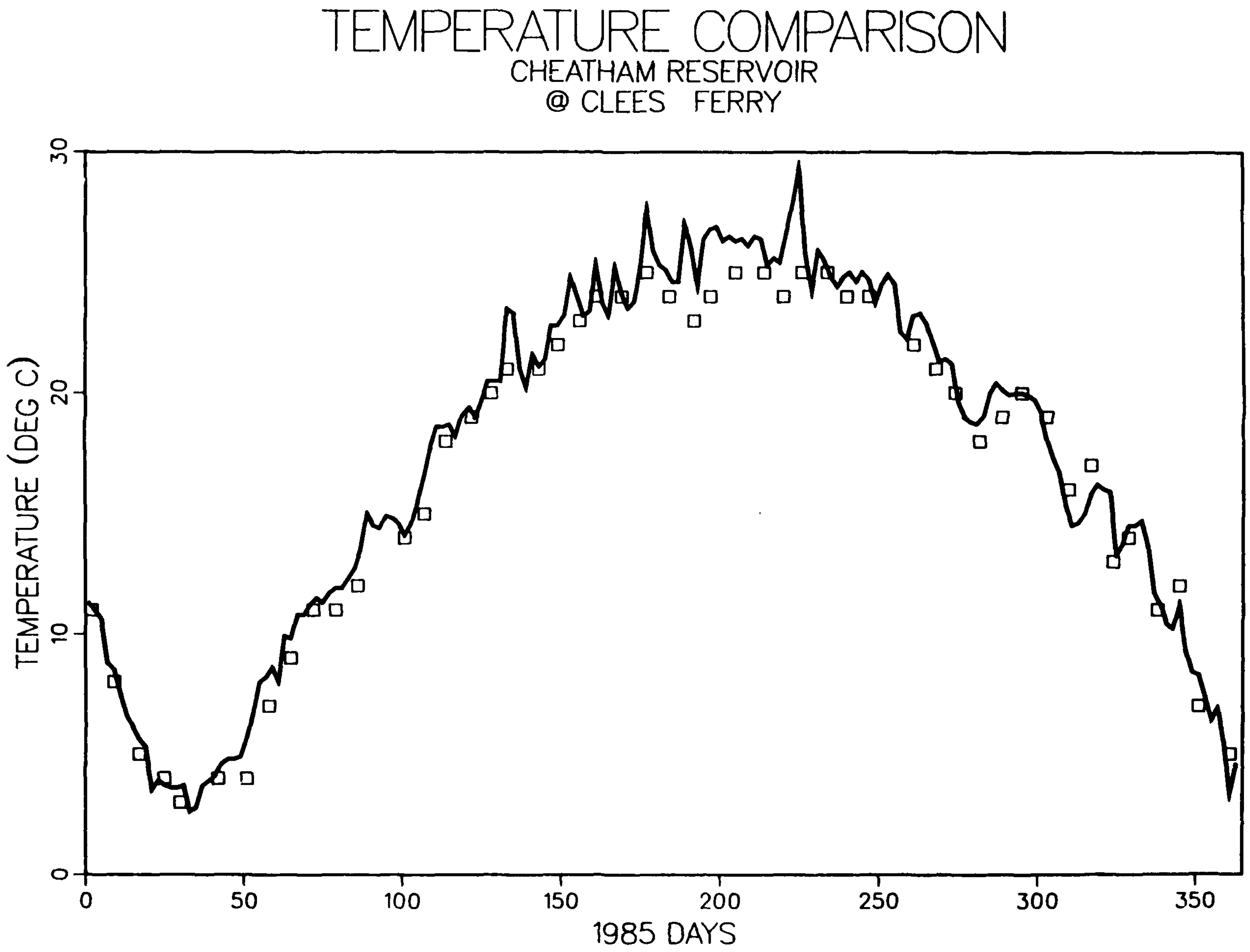

TEMPERATURE COMPARISON
CHEATHAM RESERVOIR
@ CLEES FERRY
TEMPERATURE (DEG C)
0
10
20
30
0
50
100
150
200
250
300
350
1985 DAYS

Figure AI-5

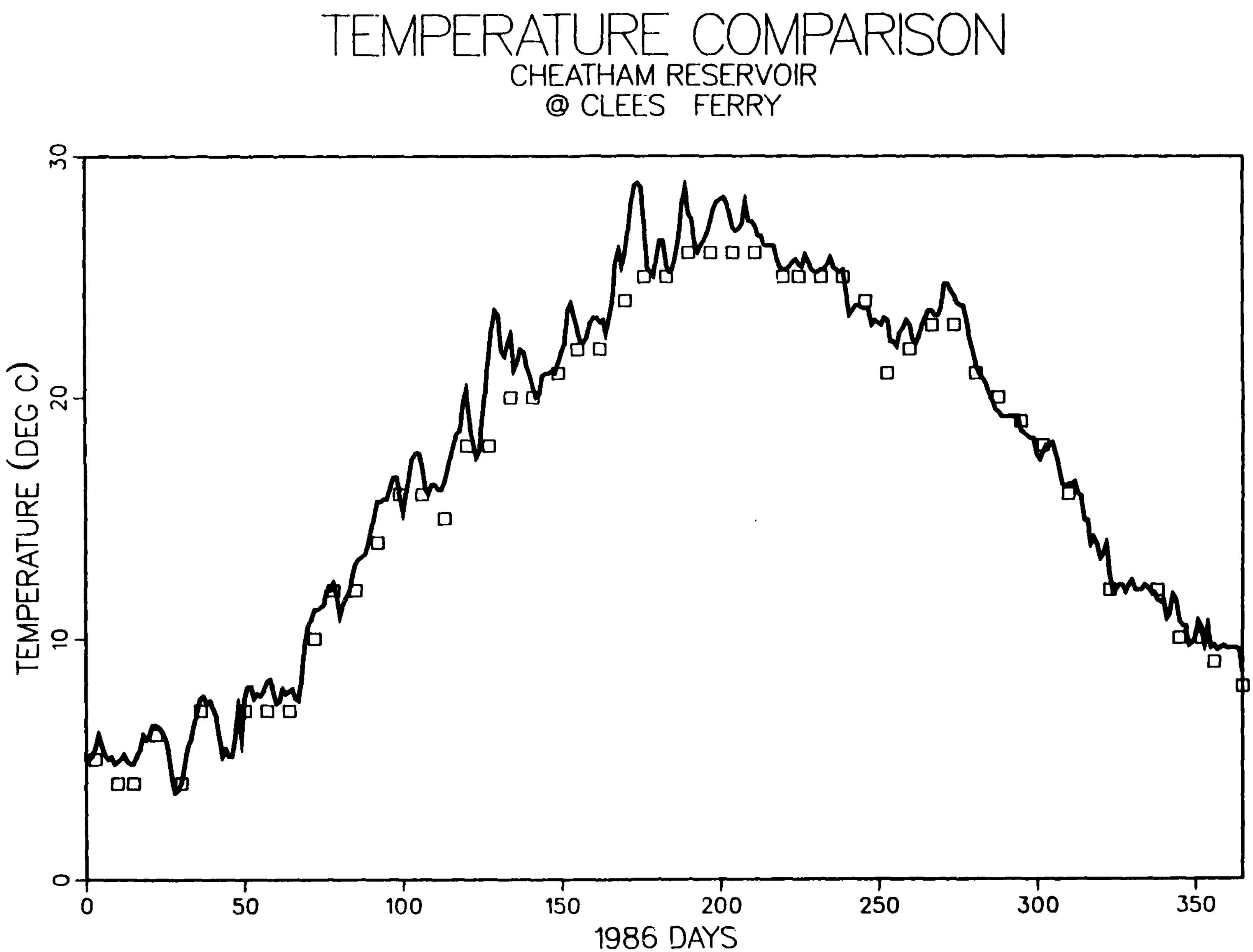
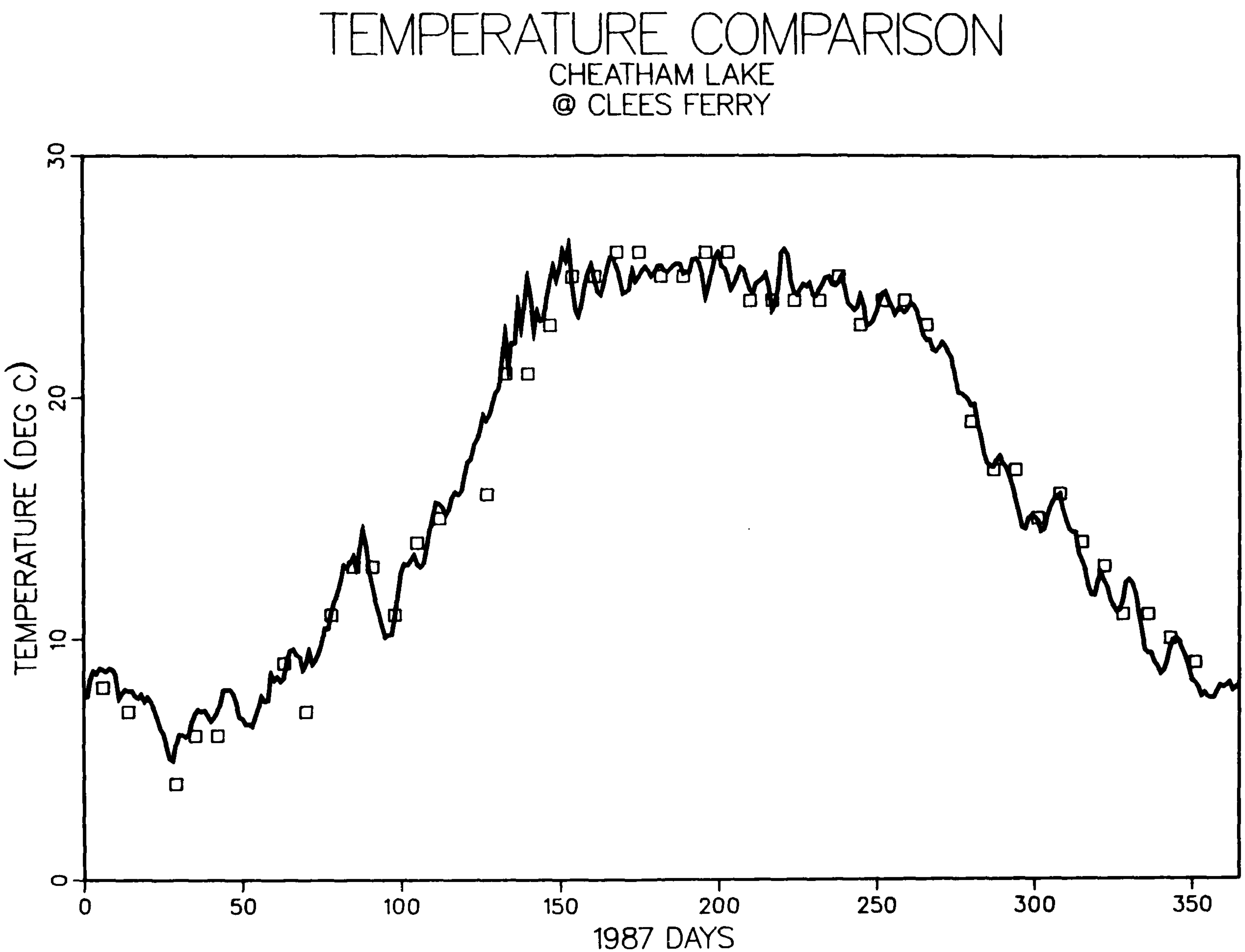

TEMPERATURE COMPARISON
CHEATHAM RESERVOIR
@ CLEES FERRY
TEMPERATURE (DEG C)
0
10
20
30
0
50
100
150
200
250
300
350
1986 DAYS

FIGURE AI-6



TEMPERATURE COMPARISON
CHEATHAM LAKE
@ CLEES FERRY
TEMPERATURE (DEG C)
0
10
20
30
0
50
100
150
200
250
300
350
1987 DAYS

Figures AI 7-9. These figures compare the water quality monitor DO data to Metro river run data just below Old Hickory Dam. There was good correlation for all years although a few periods of data disagreement were noted during late 1985, early 1986 and early 1987. It appears that more calibration of the monitor is warrented. The means for each year were statistically different, but by less than 1 mg/l.

Year	Difference in Mean Values	Prob >T
1985	0.582 mg/l	0.0001
1986	0.530	0.0072
1987	0.494	0.0141

Figure AI-7

DISSOLVED OXYGEN COMPARISON
CHEATHAM RESERVOIR
BELOW OLD HICKORY

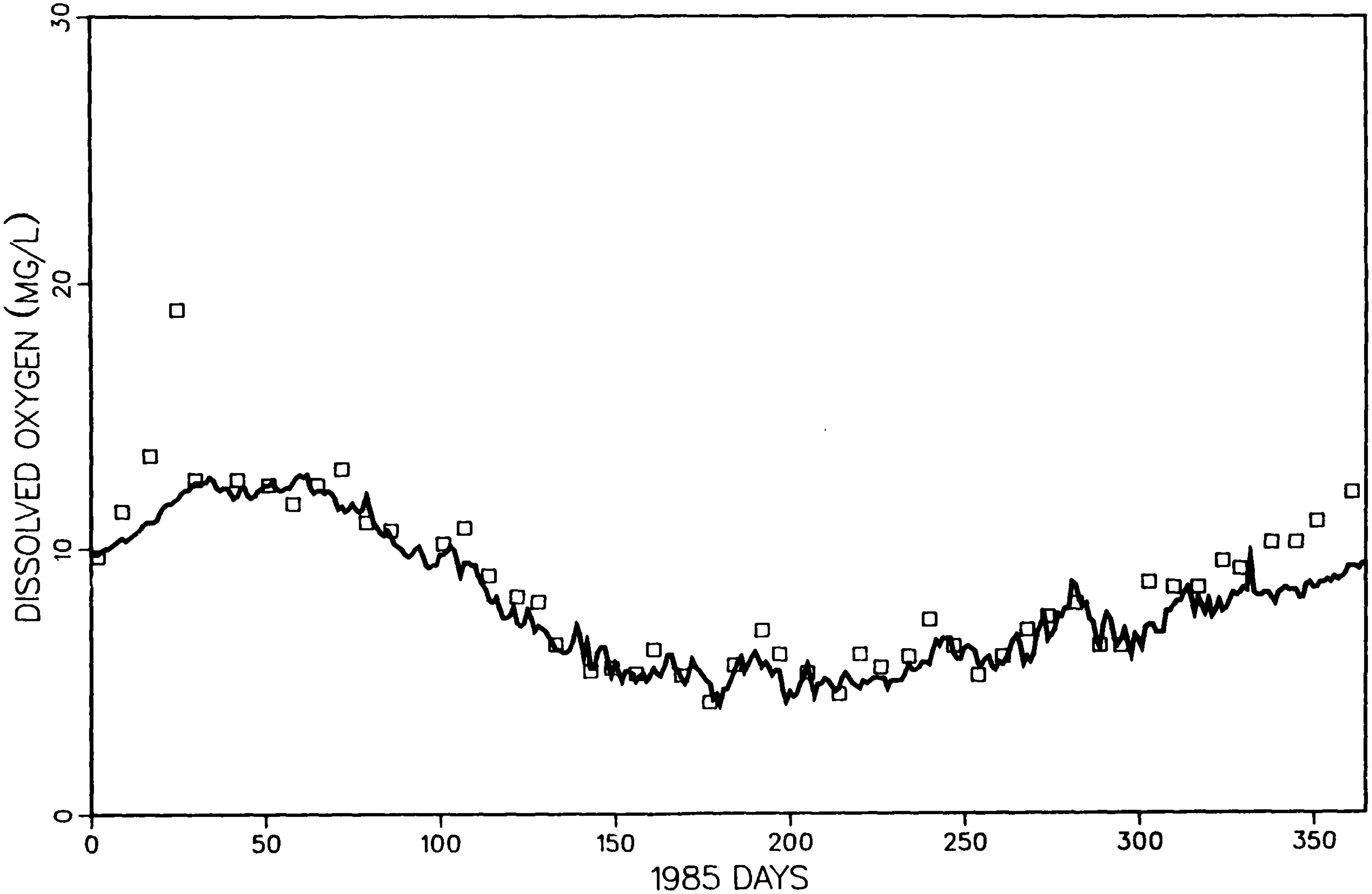


Figure AI-8

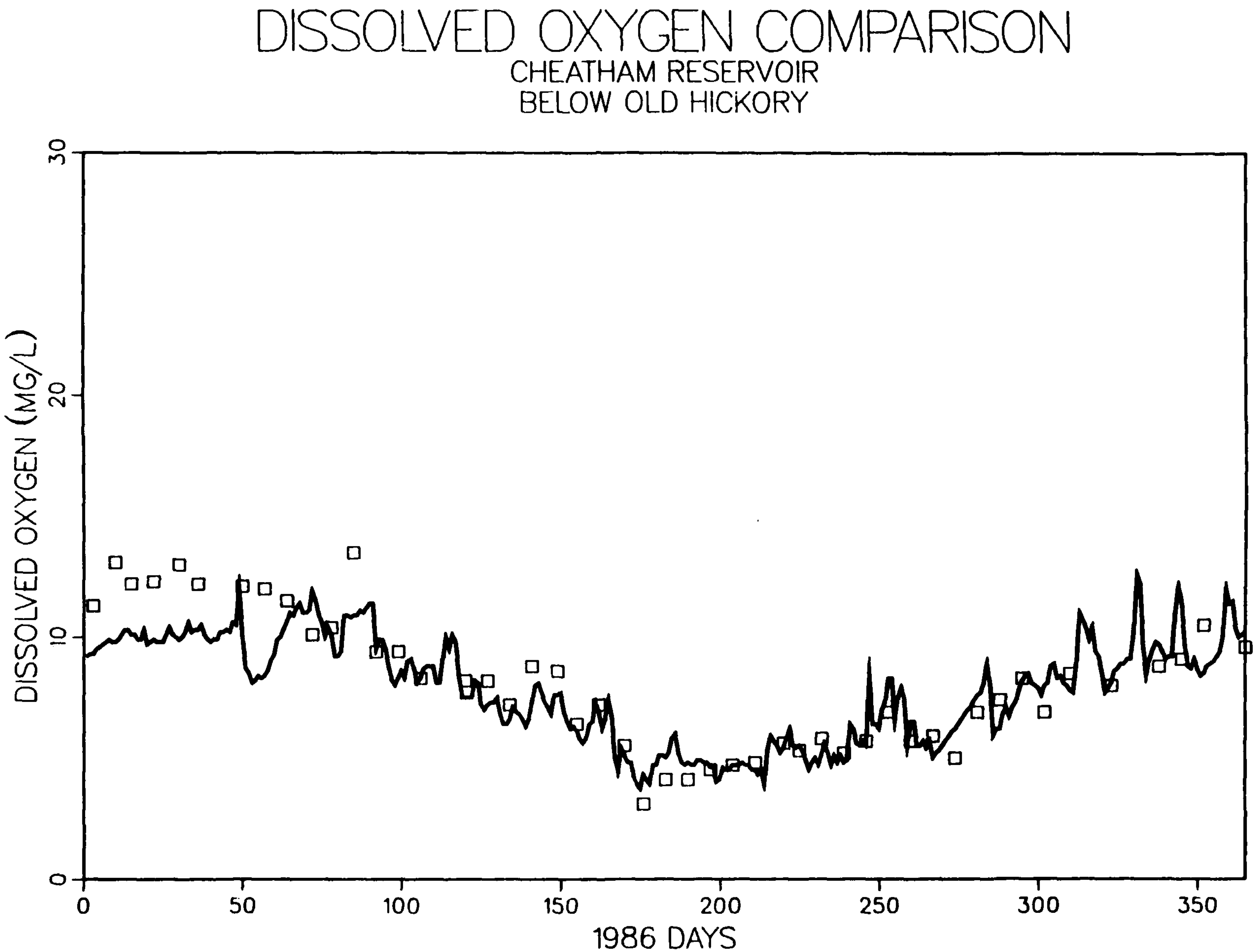
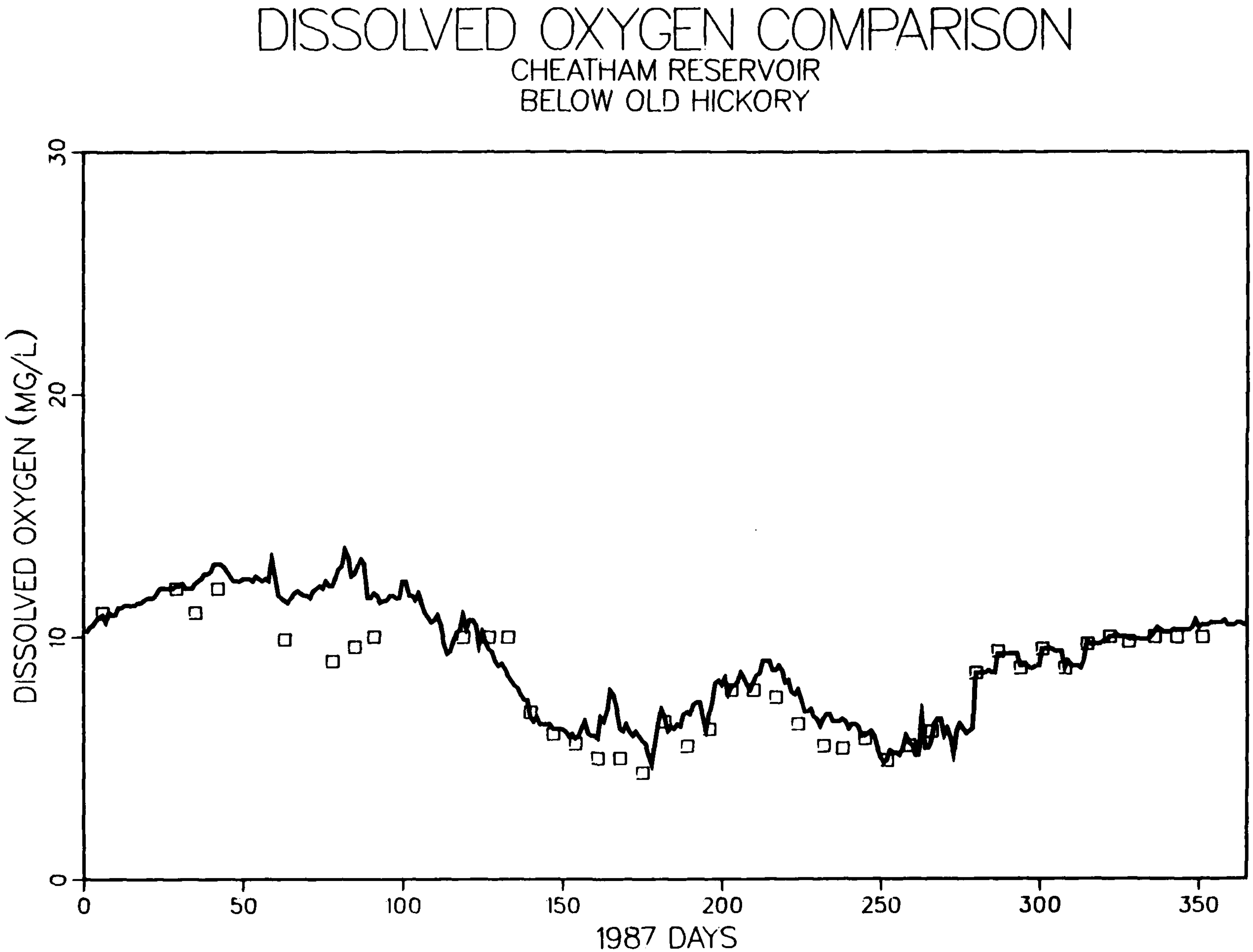

DISSOLVED OXYGEN COMPARISON
CHEATHAM RESERVOIR
BELOW OLD HICKORY
DISSOLVED OXYGEN (MG/L)
0
10
20
30
0
50
100
150
200
250
300
350
1986 DAYS

Figure AI-9


DISSOLVED OXYGEN COMPARISON
CHEATHAM RESERVOIR
BELOW OLD HICKORY
DISSOLVED OXYGEN (MG/L)
0
10
20
30
0
50
100
150
200
250
300
350
1987 DAYS

Figures AI 10-12. These figures show the relationships between BETTER predictions of dissolved oxygen and Metro river run data at Clees Ferry. There was good correlation between predicted and observed values. The means were statistically different for all years, but by less than 1 mg/l.

Year	Difference in Means	Prob >T
1985	0.758 mg/l	0.0001
1986	0.494	0.0141
1987	0.546	0.0003

Figure AI-10

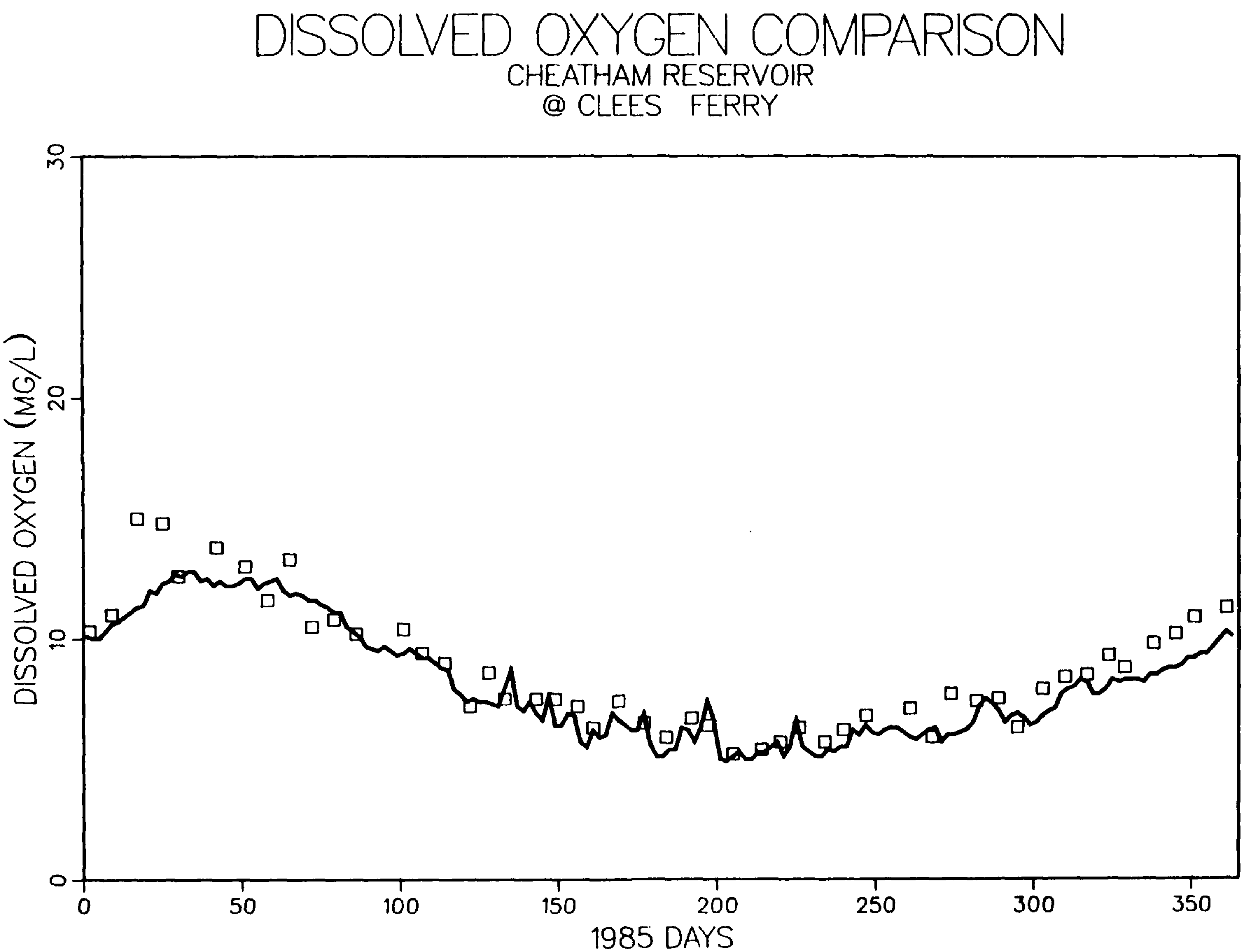

DISSOLVED OXYGEN COMPARISON
CHEATHAM RESERVOIR
@ CLEES FERRY
DISSOLVED OXYGEN (MG/L)
0
10
20
30
0
50
100
150
200
250
300
350
1985 DAYS

Figure AI-11

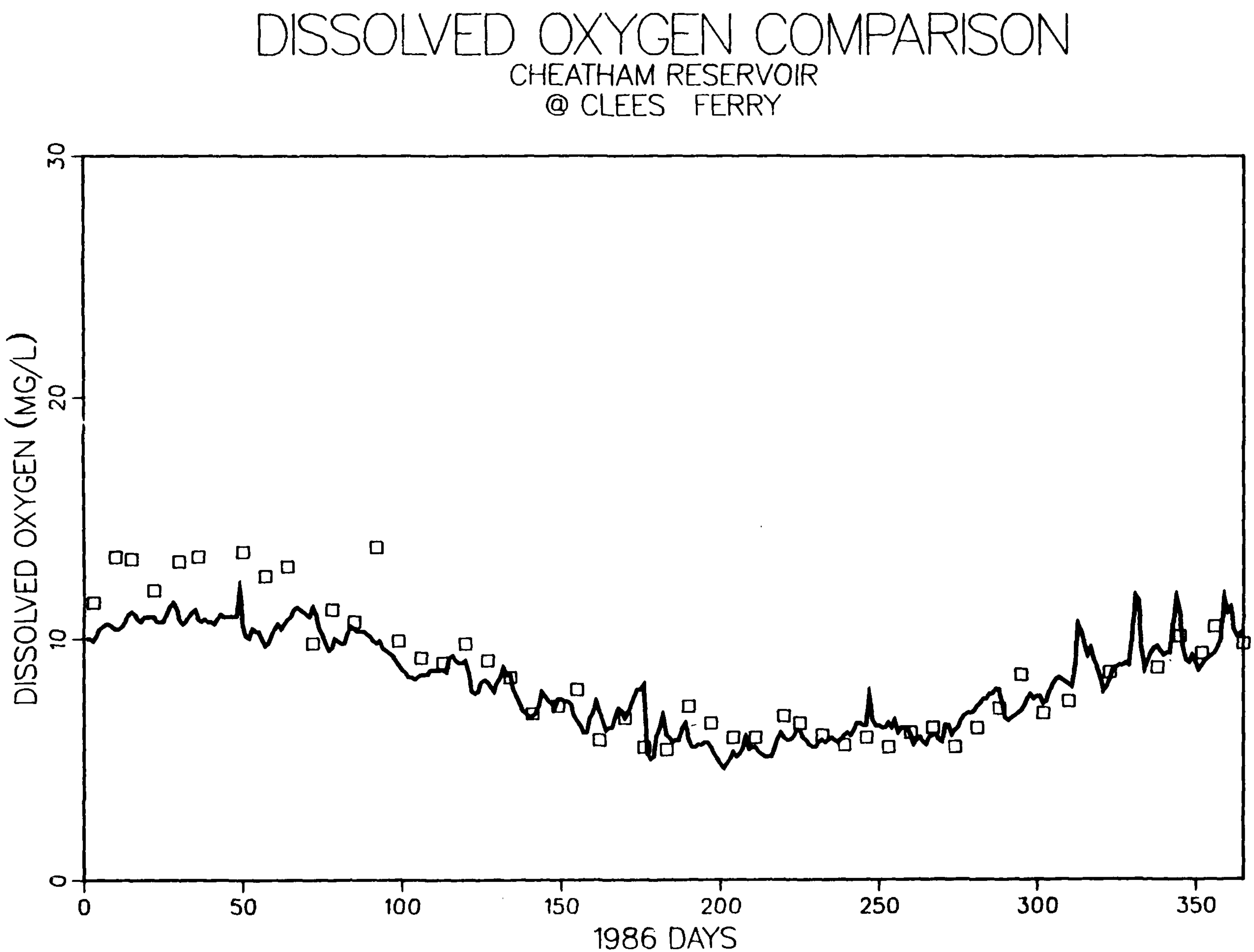
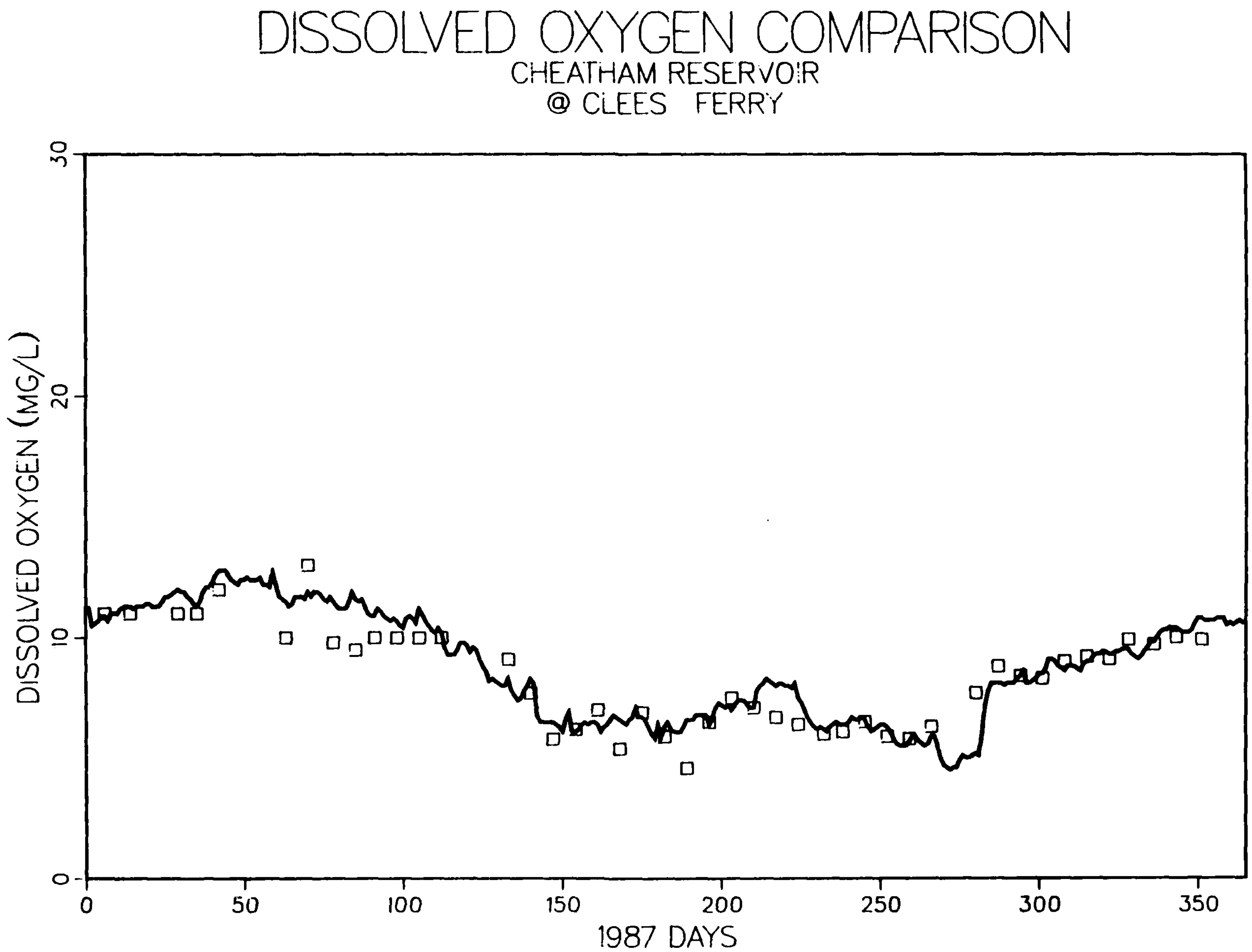

DISSOLVED OXYGEN COMPARISON
CHEATHAM RESERVOIR
@ CLEES FERRY
DISSOLVED OXYGEN (MG/L)
0
10
20
30
0
50
100
150
200
250
300
350
1986 DAYS

Figure AI-12



DISSOLVED OXYGEN COMPARISON
CHEATHAM RESERVOIR
@ CLEES FERRY
DISSOLVED OXYGEN (MG/L)
0
10
20
30
0
50
100
150
200
250
300
350
1987 DAYS

<u>Figures AI 13-15</u> - For suspended solids, the Metro river run data were used as the model input. Thus, there is "perfect" agreement.

Figure AI-13

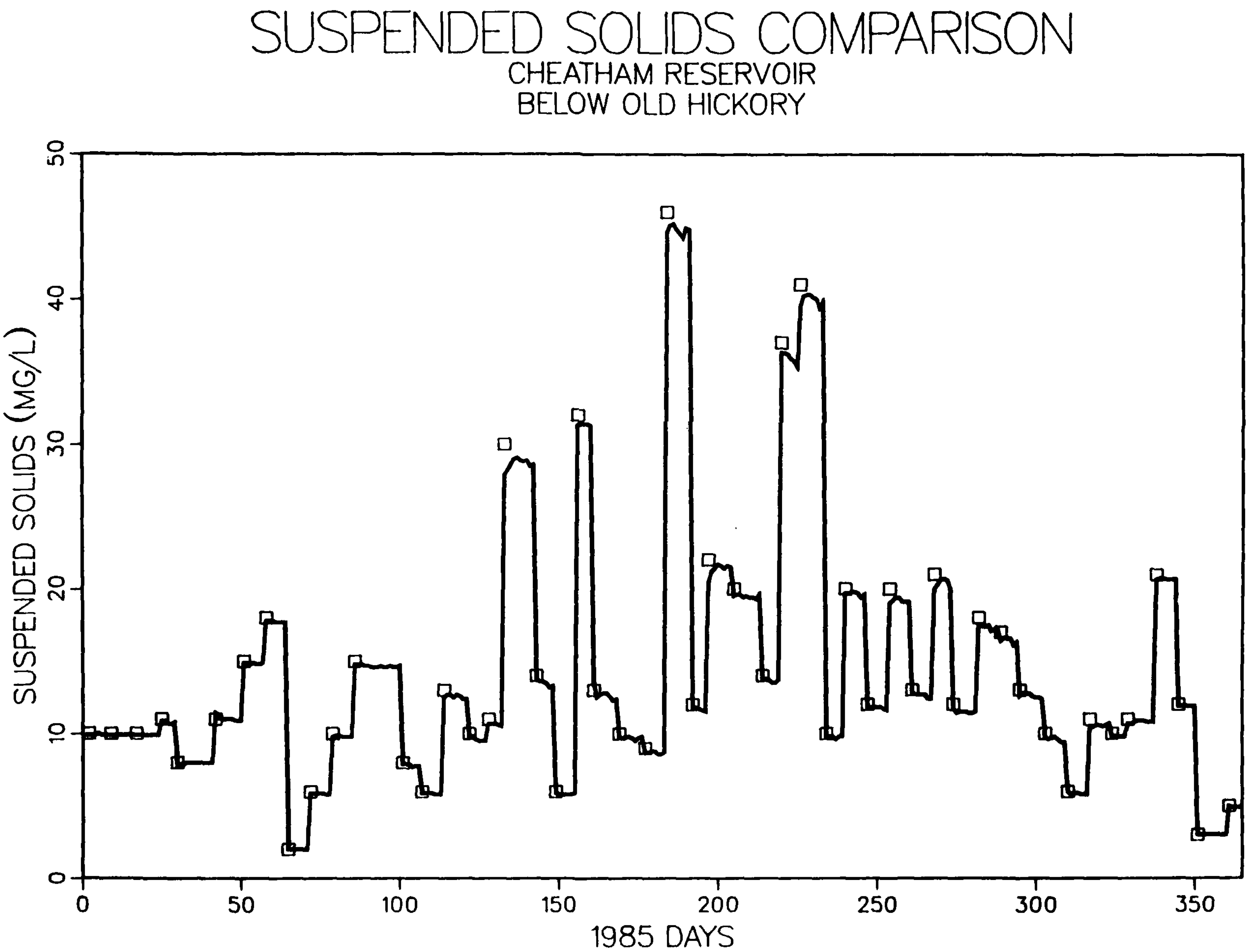

SUSPENDED SOLIDS COMPARISON
CHEATHAM RESERVOIR
BELOW OLD HICKORY
SUSPENDED SOLIDS (MG/L)
0
10
20
30
40
50
0
50
100
150
200
250
300
350
1985 DAYS

Figure AI-14

SUSPENDED SOLIDS COMPARISON

CHEATHAM RESERVOIR
BELOW OLD HICKORY

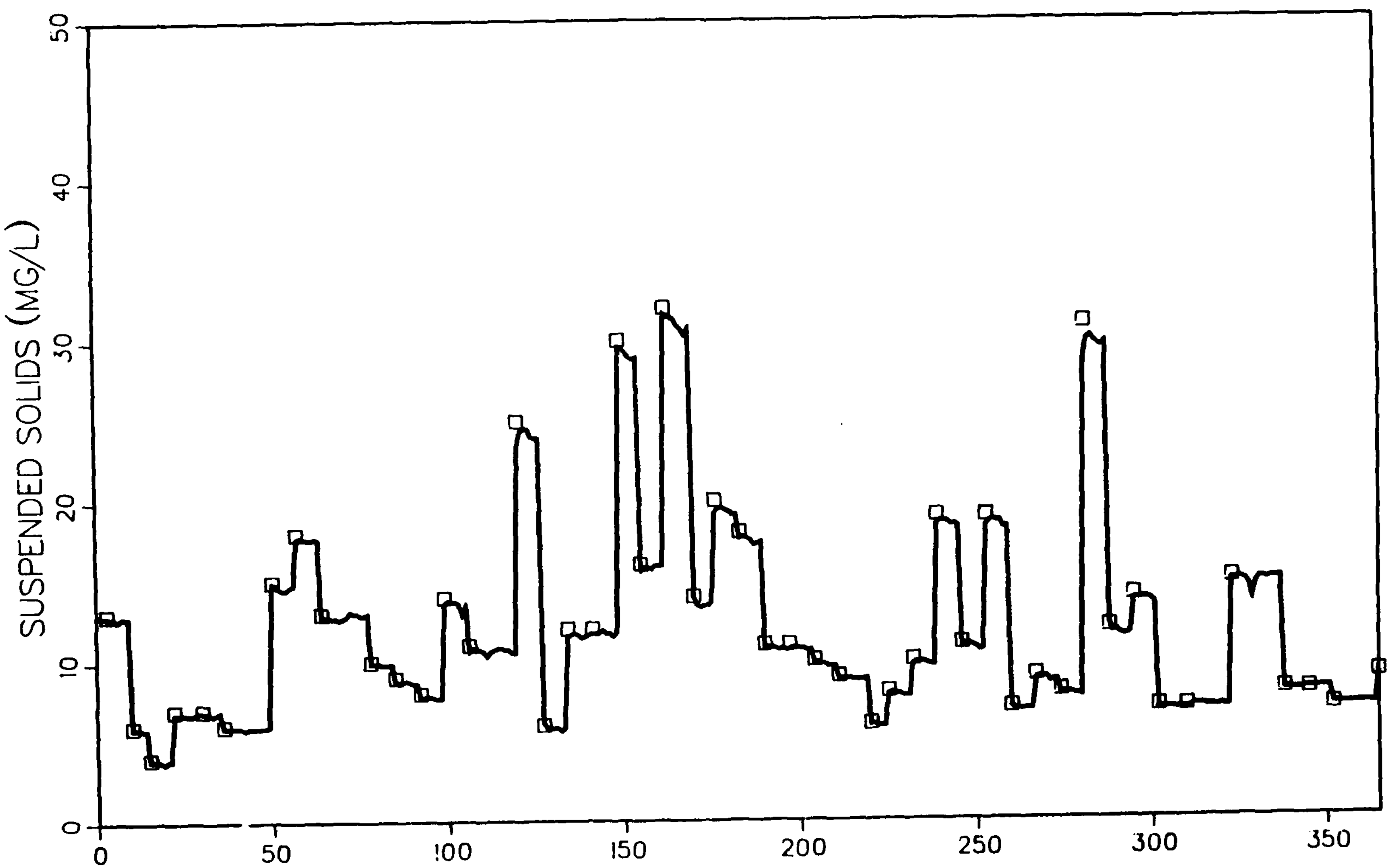
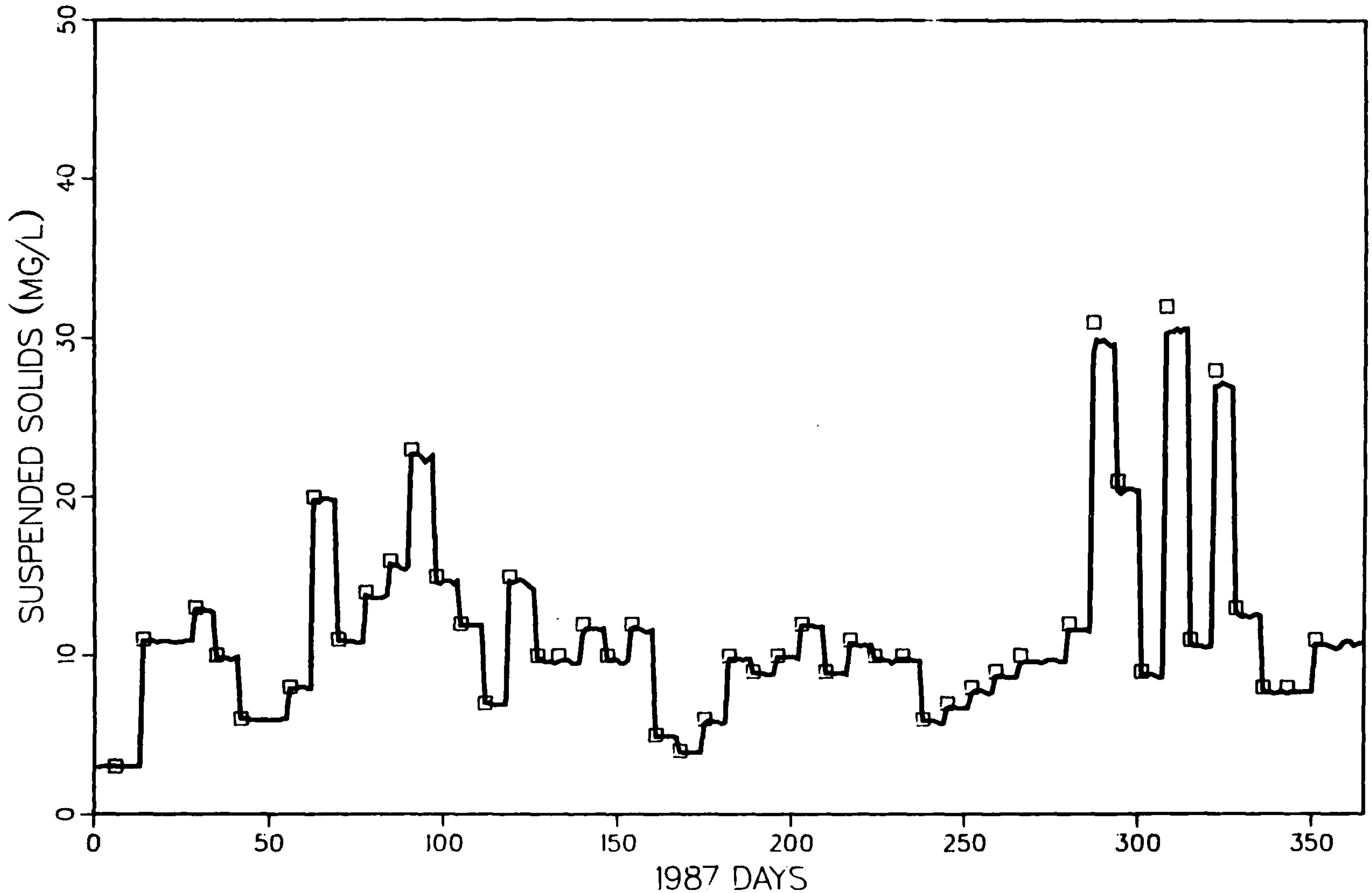


Figure AI-15

SUSPENDED SOLIDS COMPARISON

CHEATHAM RESERVOIR
BELOW OLD HICKORY



<u>Figures AI 16-18</u>. The modeled suspended solids and measured SS values by the Metro river run at Clees Ferry are shown. Table 1 shows that correlation was only fair to poor. The means were statistically different. Thus, there was only a limited capability to use BETTER for suspended solids predictions on Cheatham Reservoir.

Year	R-value	Difference in means	Prob >T
1985	-0.106	0.300 mg/l	0.0006
1986	0.486	0.149	0.0333
1987	0.442	0.149	0.0333

Figure A1-16

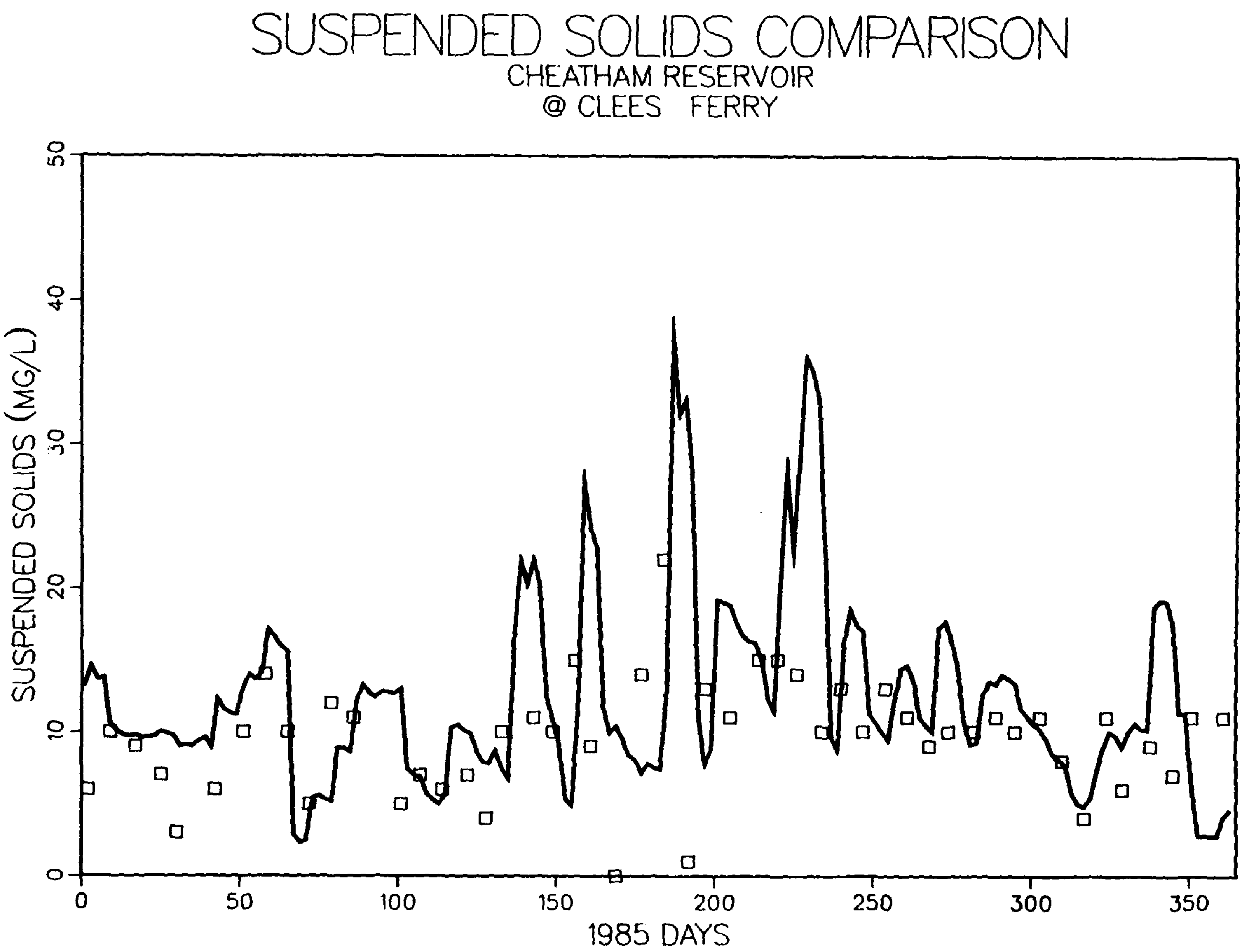

SUSPENDED SOLIDS COMPARISON
CHEATHAM RESERVOIR
@ CLEES FERRY
SUSPENDED SOLIDS (MG/L)
0
10
20
30
40
50
0
50
100
150
200
250
300
350
1985 DAYS

Figure AI-17

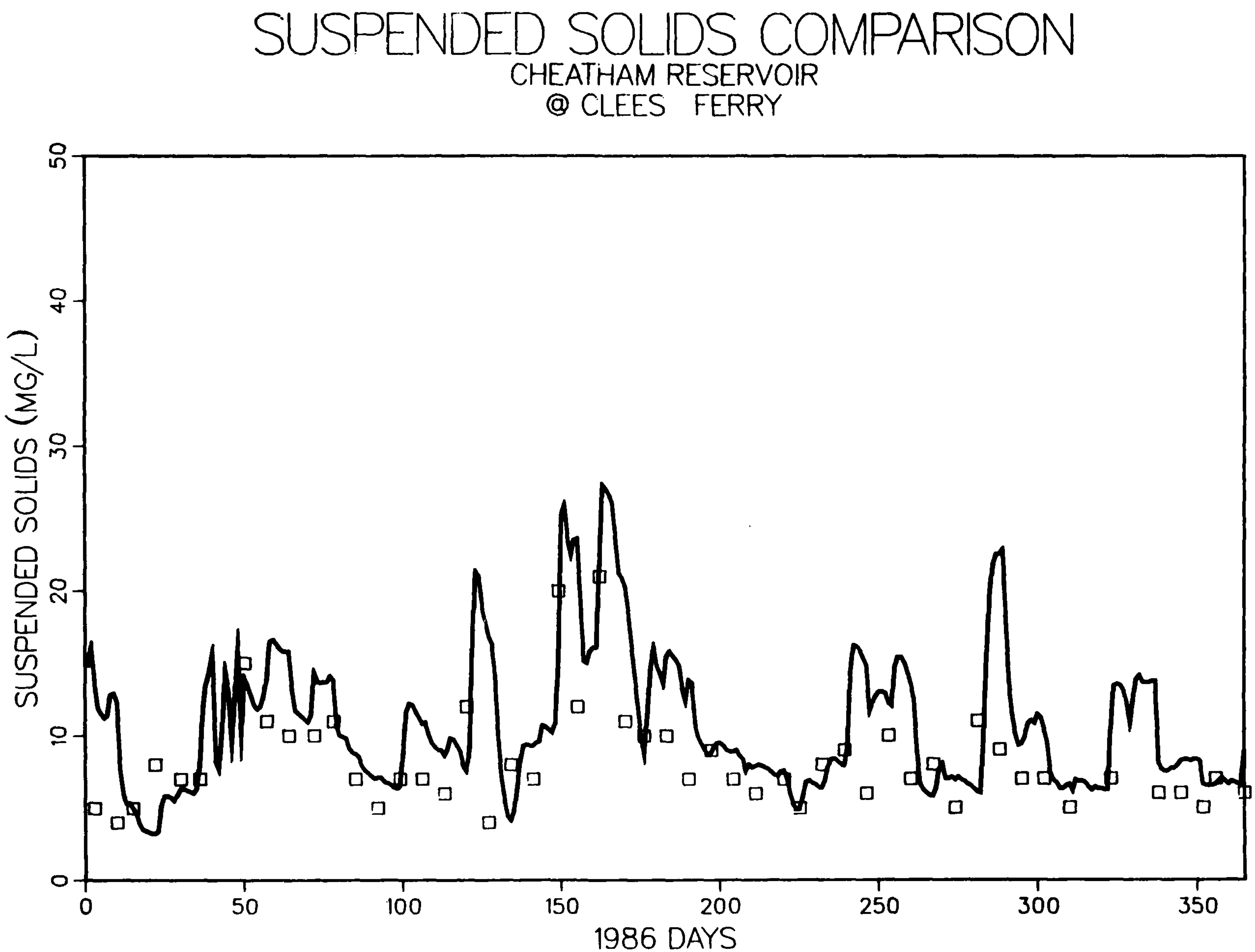
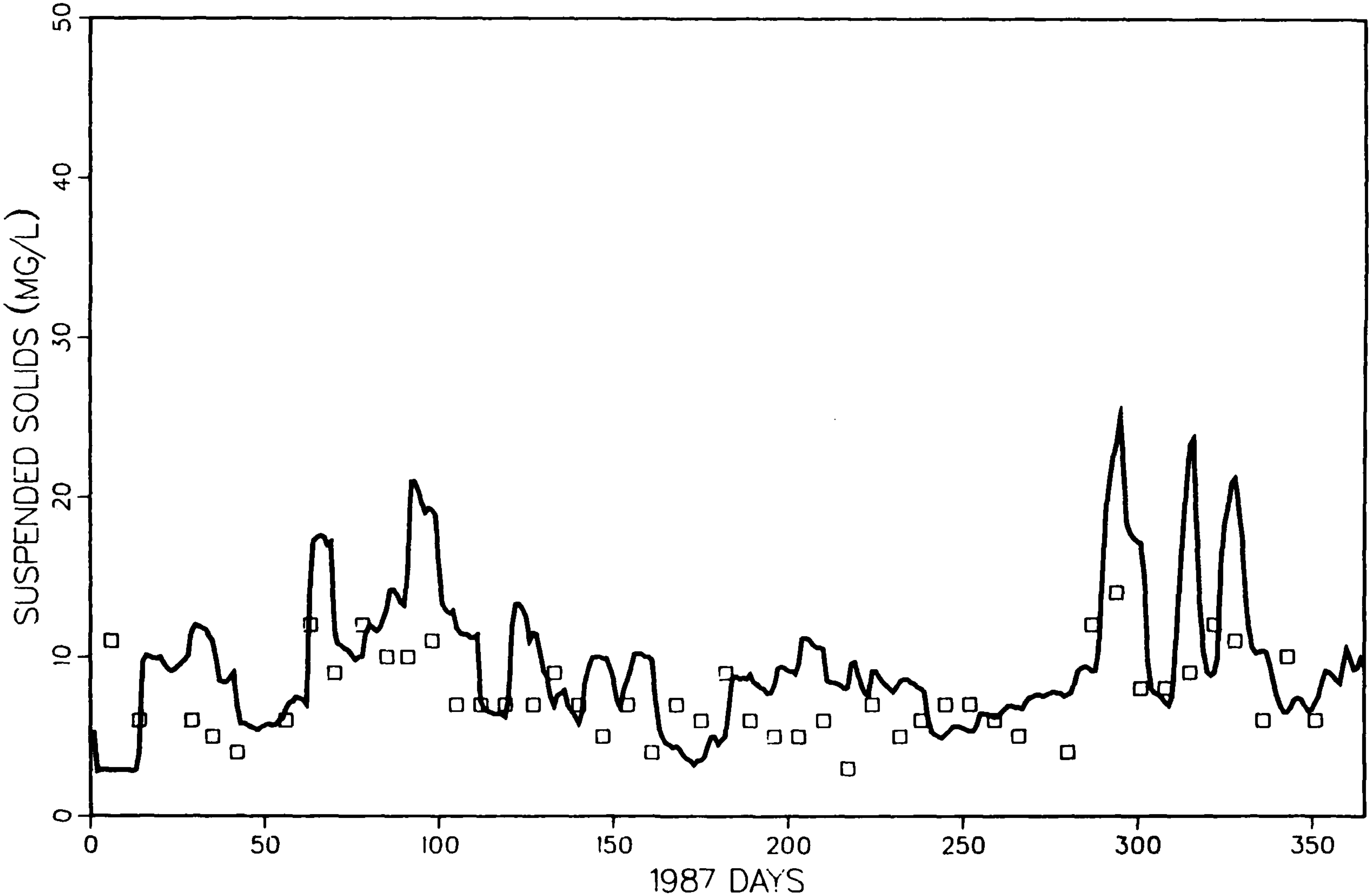

SUSPENDED SOLIDS COMPARISON
CHEATHAM RESERVOIR
@ CLEES FERRY
SUSPENDED SOLIDS (MG/L)
0
10
20
30
40
50
0
50
100
150
200
250
300
350
1986 DAYS

Figure AI-18

SUSPENDED SOLIDS COMPARISON

CHEATHAM RESERVOIR
@ CLEES FERRY



Figures AI 19-21. These figures show very poor correlation between the pH recorded by the water quality monitor and the Metro river run pH values below Old Hickory. There was pooor correlation during 1985 and 1986 although the mean values were not statistically different. During 1987, the river run data were used as input so the correlation is very good. Without better correlation between the monitor and river run, BETTER cannot be expected to produce better results.

Year	R-value	Difference in Means	Prob > T
1985	0.241	0.0239	0.6067
1986	0.429	0.479	0.3436
1987	0.999	0.333	0.0002

Figure AI-19

pH COMPARISON
CHEATHAM RESERVOIR
BELOW OLD HICKORY

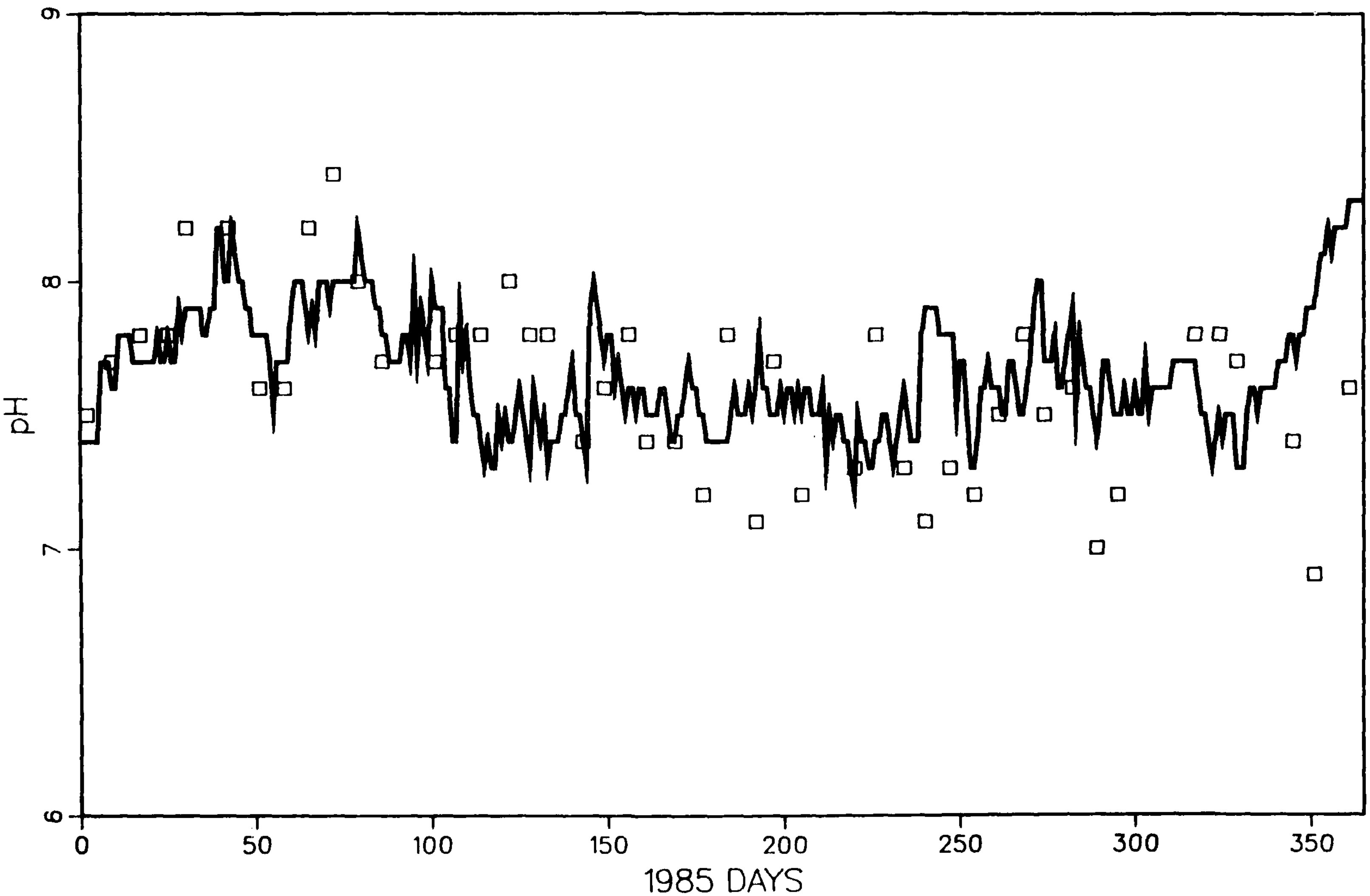


Figure AI-20

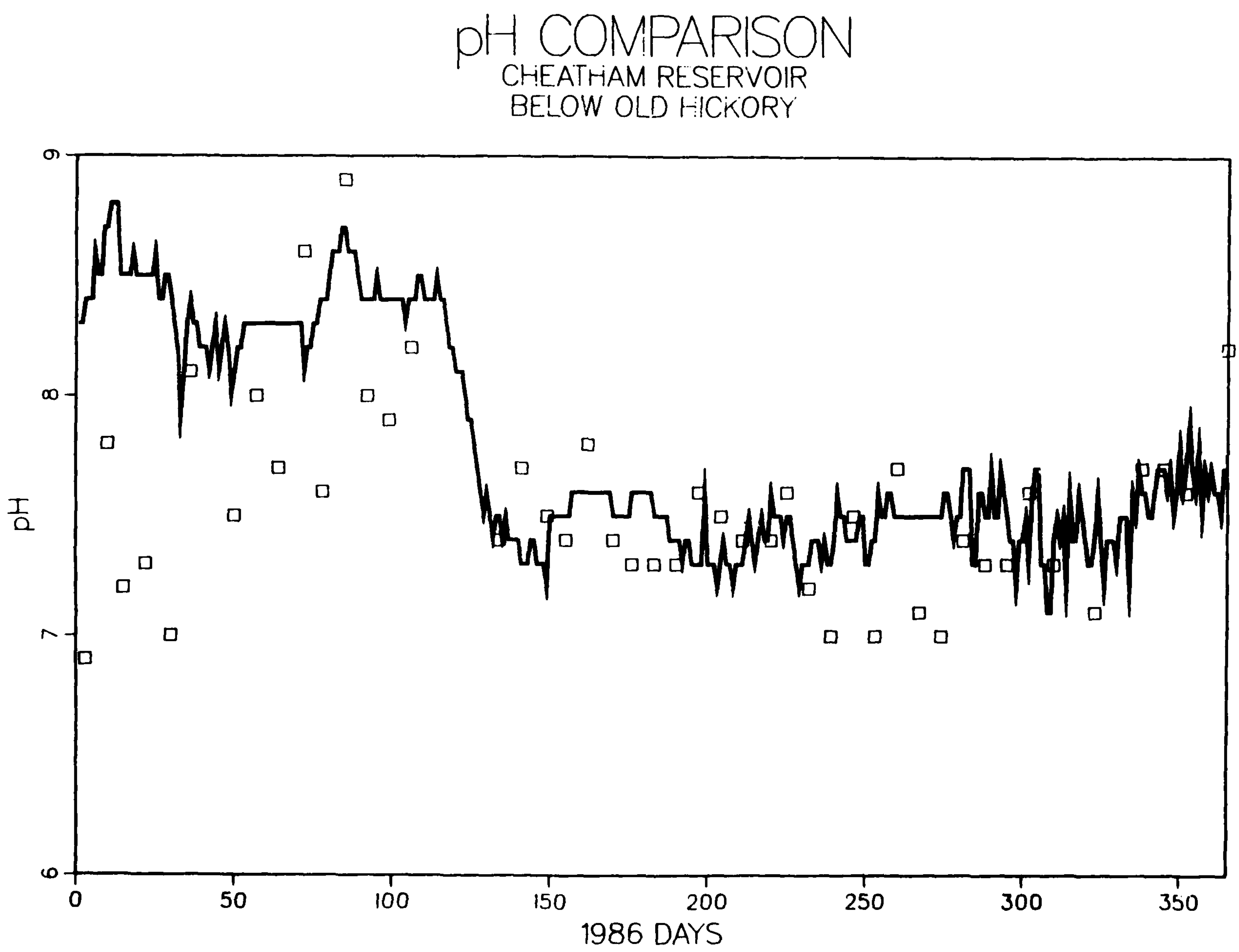
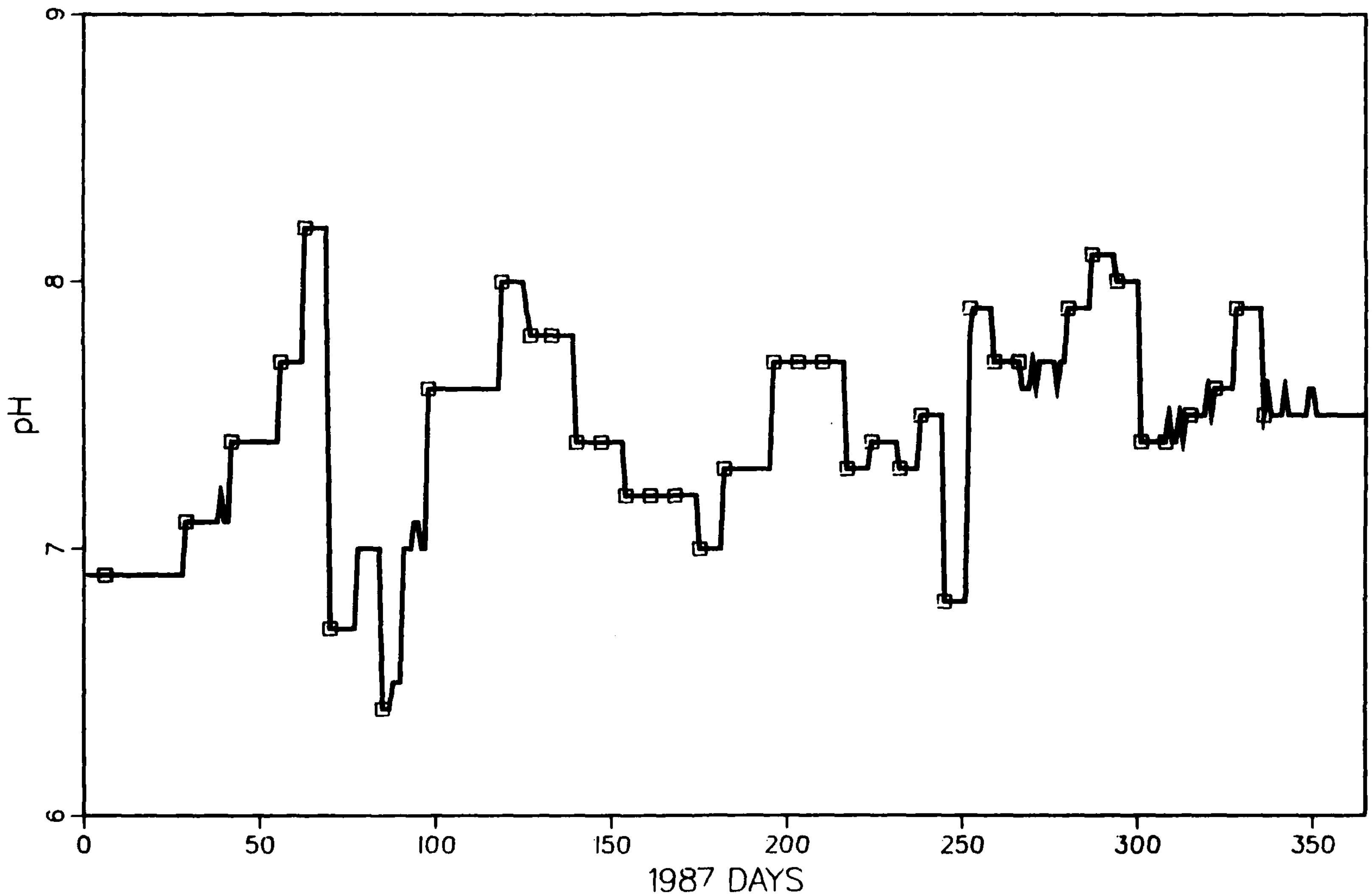

pH COMPARISON
CHEATHAM RESERVOIR
BELOW OLD HICKORY
9
8
7
6
pH
0
50
100
150
200
250
300
350
1986 DAYS

Figure AI-21

pH COMPARISON
CHEATHAM RESERVOIR
BELOW OLD HICKORY



Figures AI 22-24. The pH comparisons at Clees Ferry are shown by these figures. The correlations for 1985 were poor, for 1986 fair, and for 1987 are very poor. The means were statistically similar during 1986. In general, BETTER predicts pH values between 7 and 8.3 while river run values run both higher and lower. During 1987, river run pH values were consistantly lower than BETTER values.

Year	R-value	Difference in Means	Prob >T
1985	0.335	-0.0174	0.7487
1986	0.565	-0.228	0.0020
1987	-0.024	0.003	0.3238

Figure AI-22

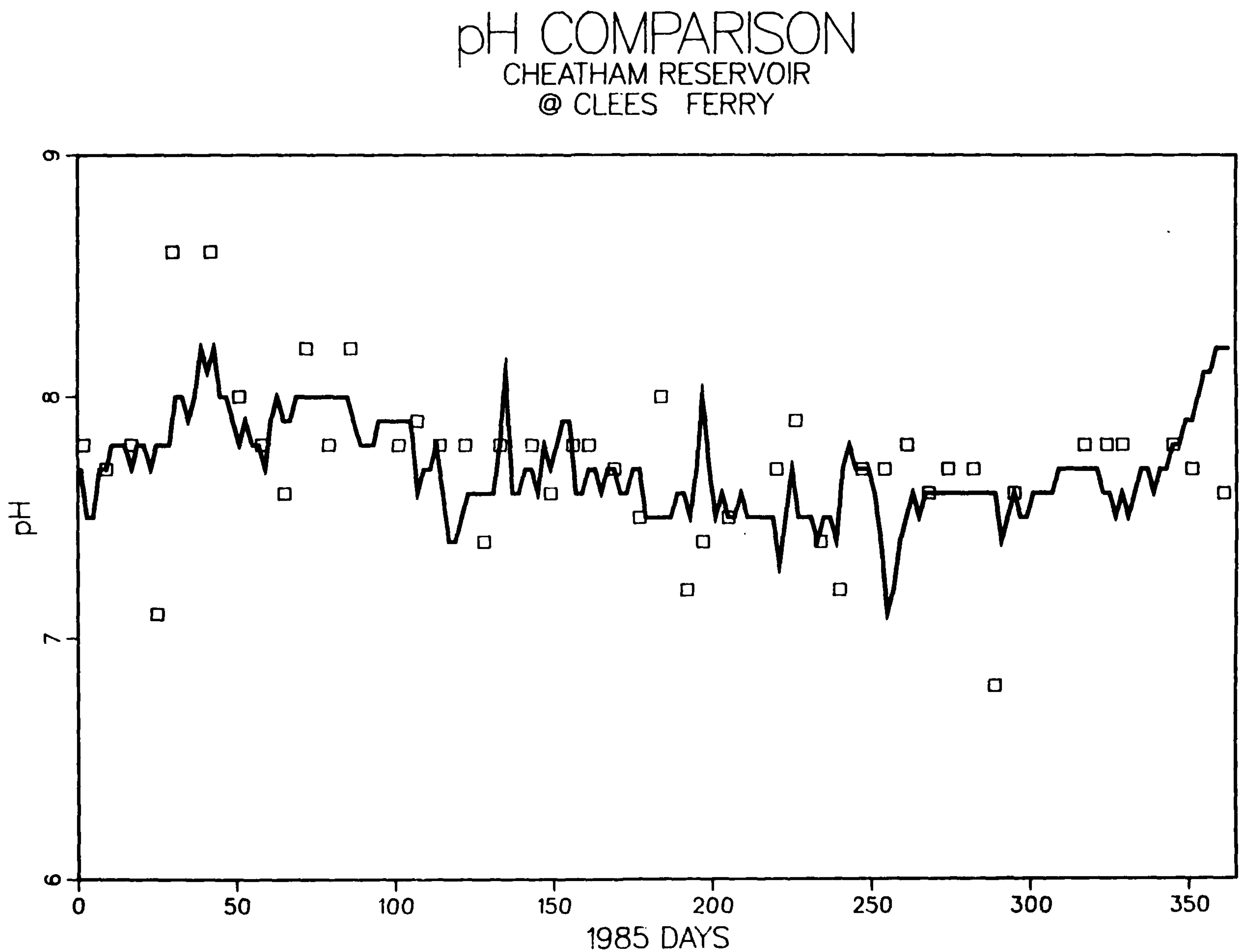

pH COMPARISON
CHEATHAM RESERVOIR
@ CLEES FERRY
9
8
7
6
pH
0
50
100
150
200
250
300
350
1985 DAYS

Figure AI-23

pH COMPARISON
CHEATHAM RESERVOIR
@ CLEES FERRY

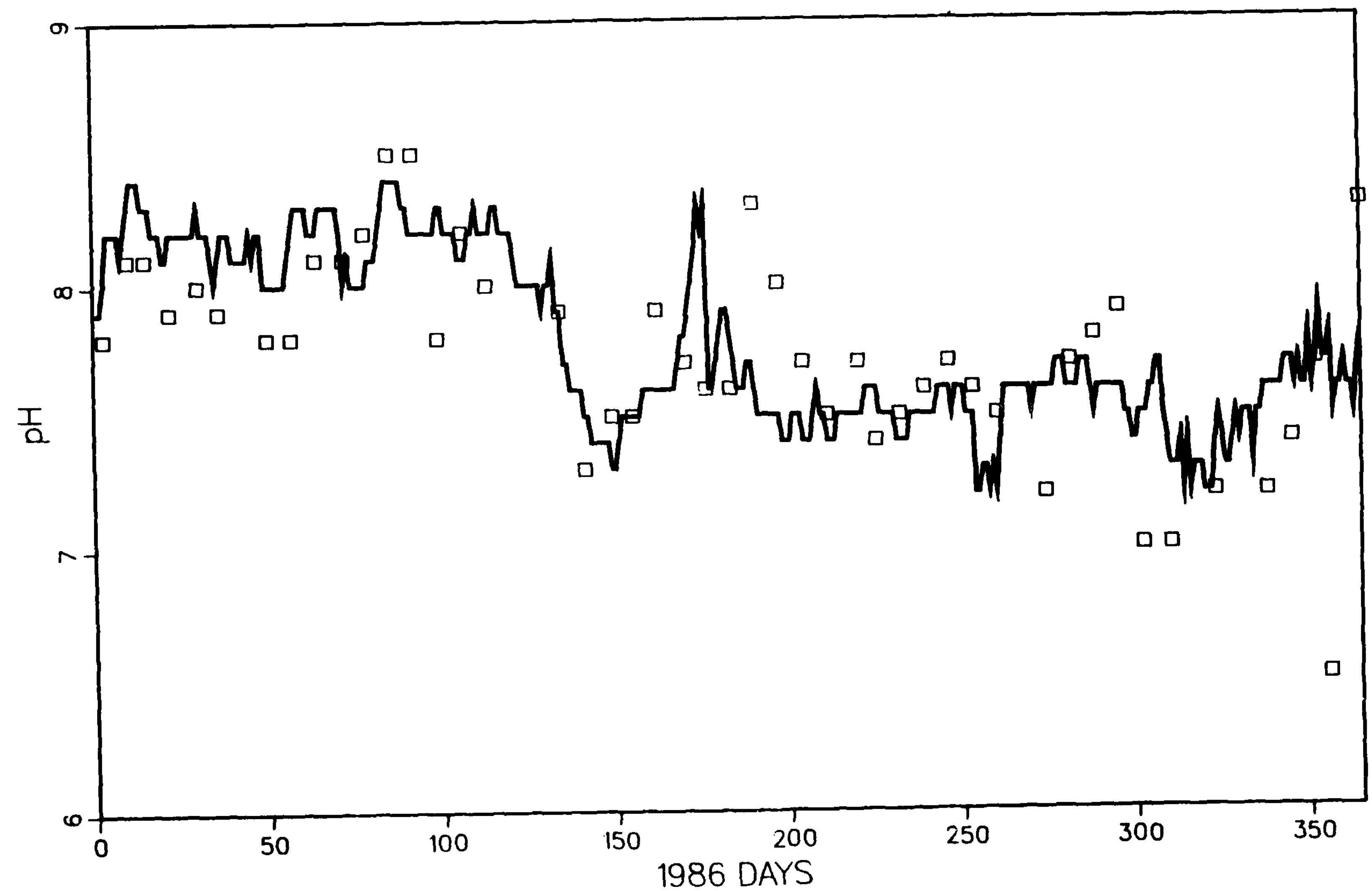
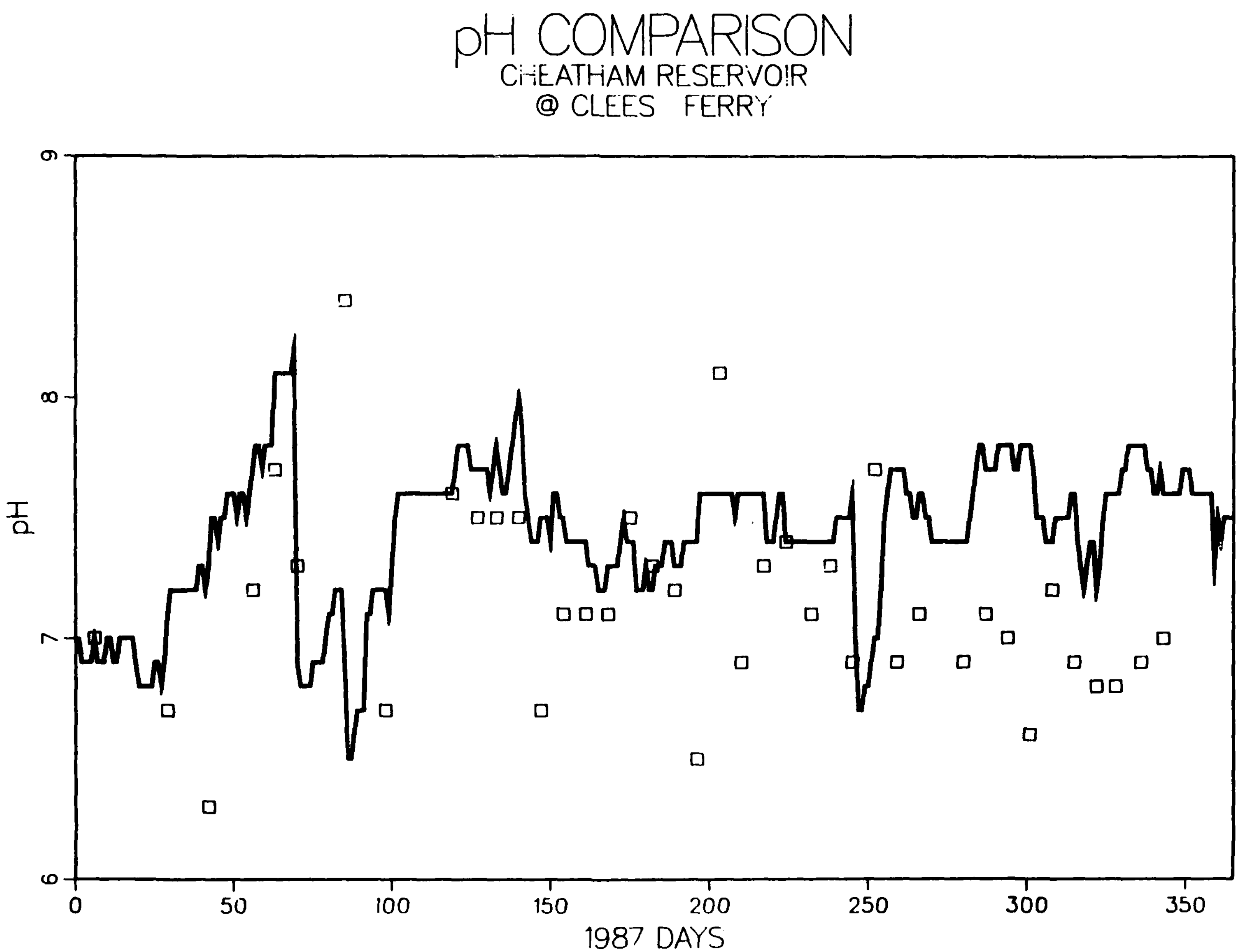


Figure AI-24


pH COMPARISON
CHEATHAM RESERVOIR
@ CLEES FERRY
pH
9
8
7
6
0
50
100
150
200
250
300
350
1987 DAYS

Figures AI 25-27. The figures show that Metro river run NH_3 data were used as model input with almost perfect correlation. The means are, of course, similar.

Figure AI-25

AMMONIA COMPARISON

CHEATHAM RESERVOIR

BELOW OLD HICKORY

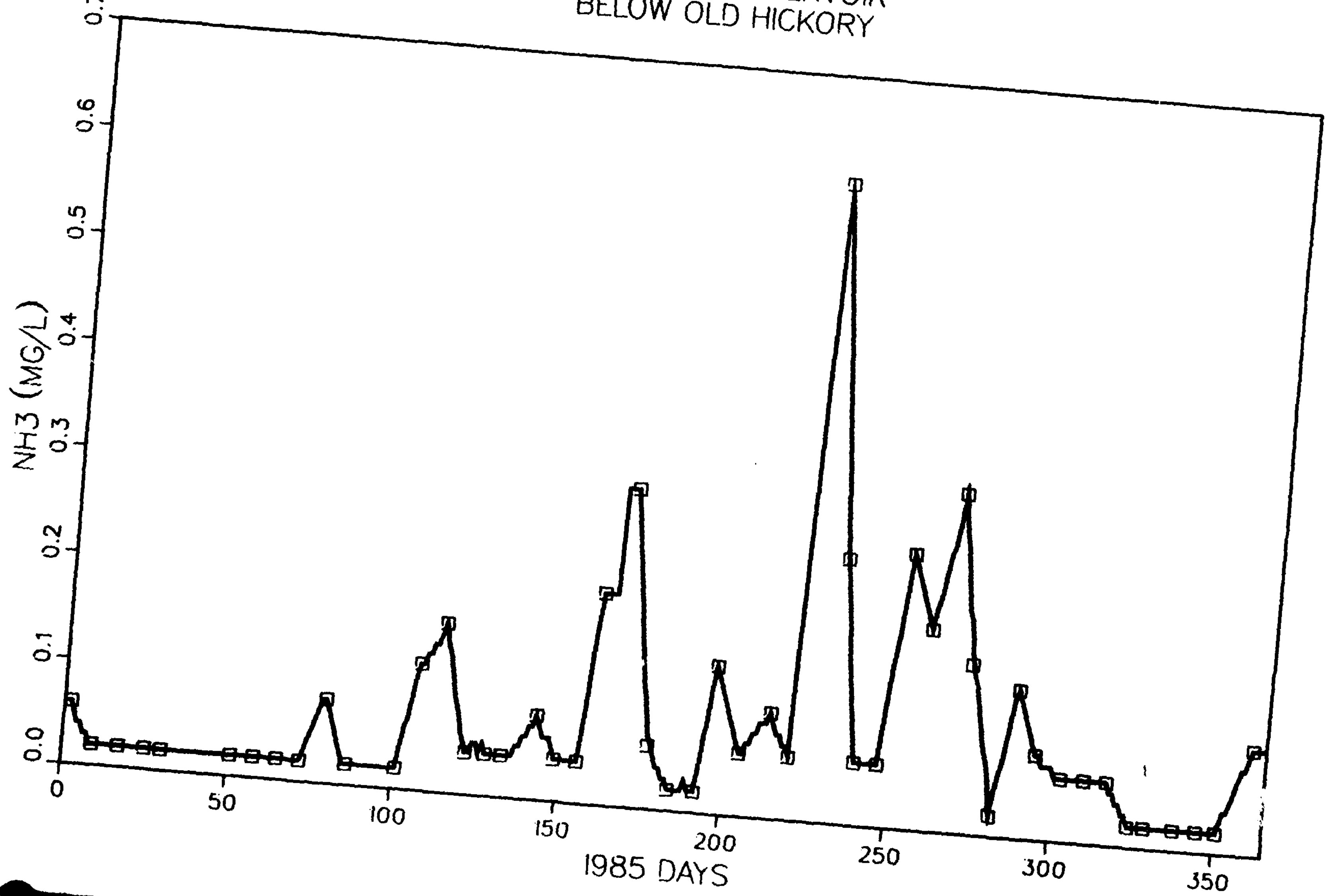


Figure AI-26

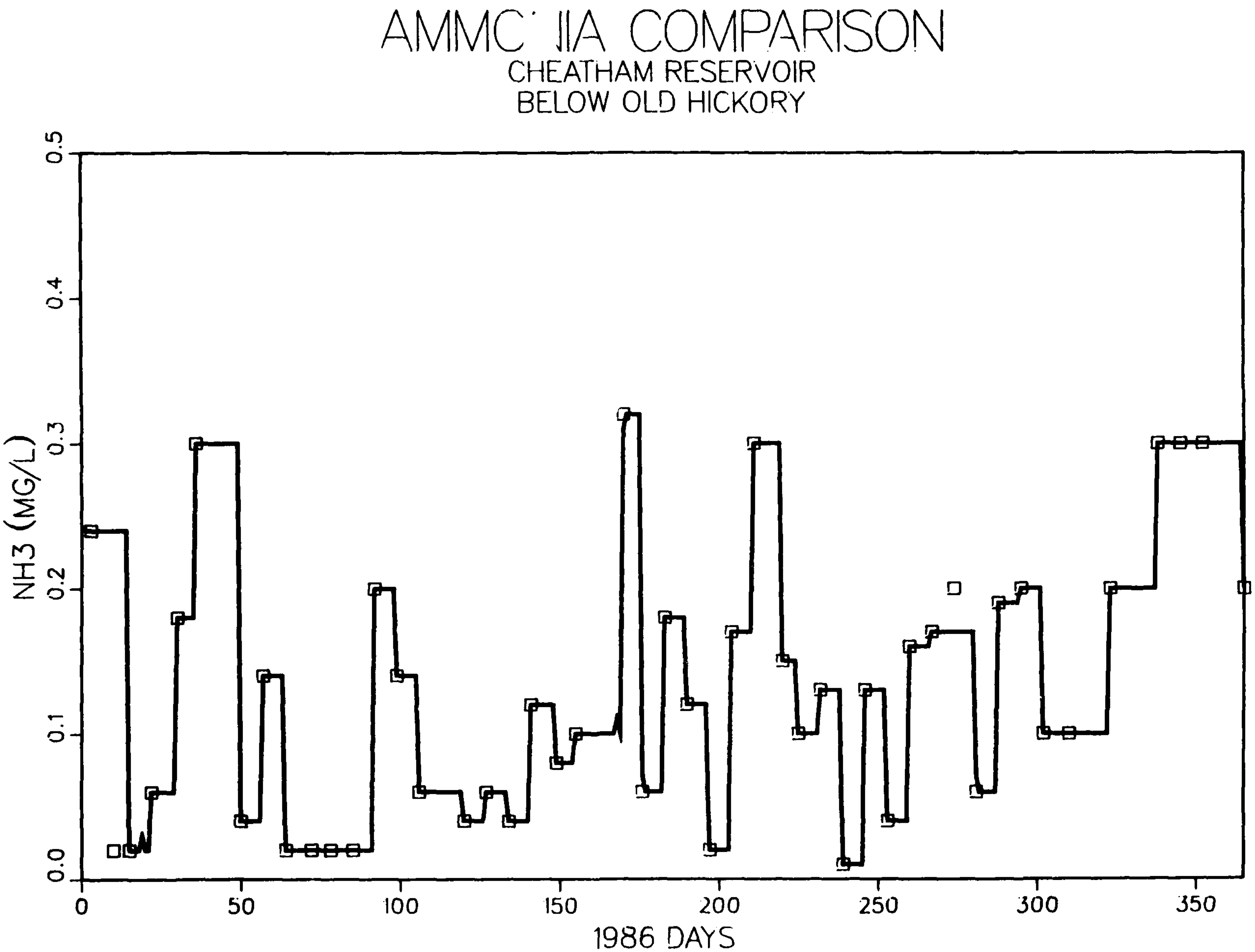
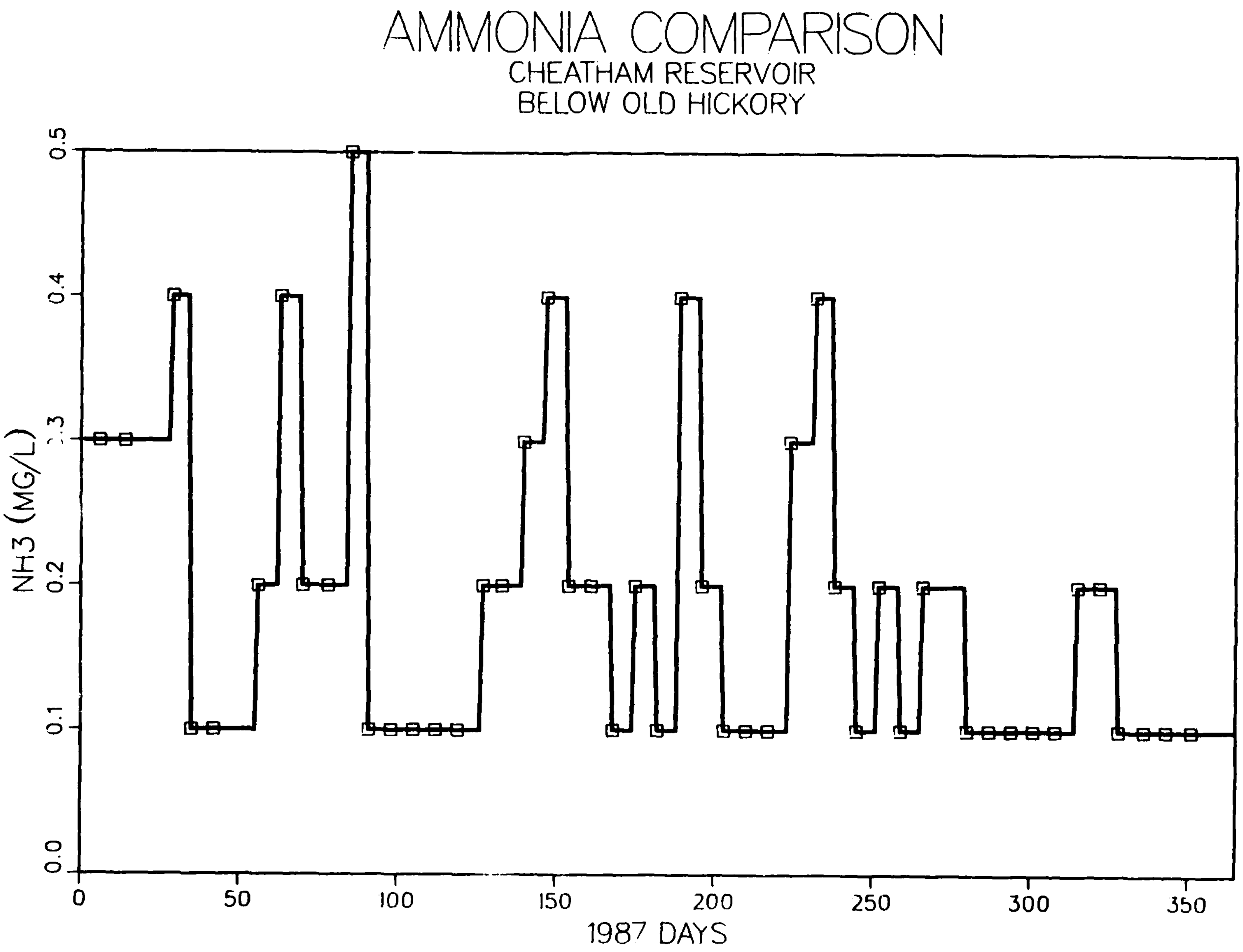

AMMC' IIA COMPARISON
CHEATHAM RESERVOIR
BELOW OLD HICKORY
NH3 (MG/L)
0.0
0.1
0.2
0.3
0.4
0.5
0
50
100
150
200
250
300
350
1986 DAYS

Figure AI-27


AMMONIA COMPARISON
CHEATHAM RESERVOIR
BELOW OLD HICKORY
NH3 (MG/L)
0.0
0.1
0.2
0.4
0.5
0
50
100
150
200
250
300
350
1987 DAYS

Figures AI 28-30. BETTER predictions of NH_3 are compared to Metro river run data by these figures. The values are only moderately correlated. The means were statistically similar during 1985 and 1986.

Year	R-values	Difference in Means	Prob >T
1985	0.333	0.000204	0.5691
1986	0.303	0.00425	0.3748
1987	0.365	0.00149	0.0067

Figure AI-28

AMMONIA COMPARISON
CHEATHAM RESERVOIR
@ CLEES FERRY

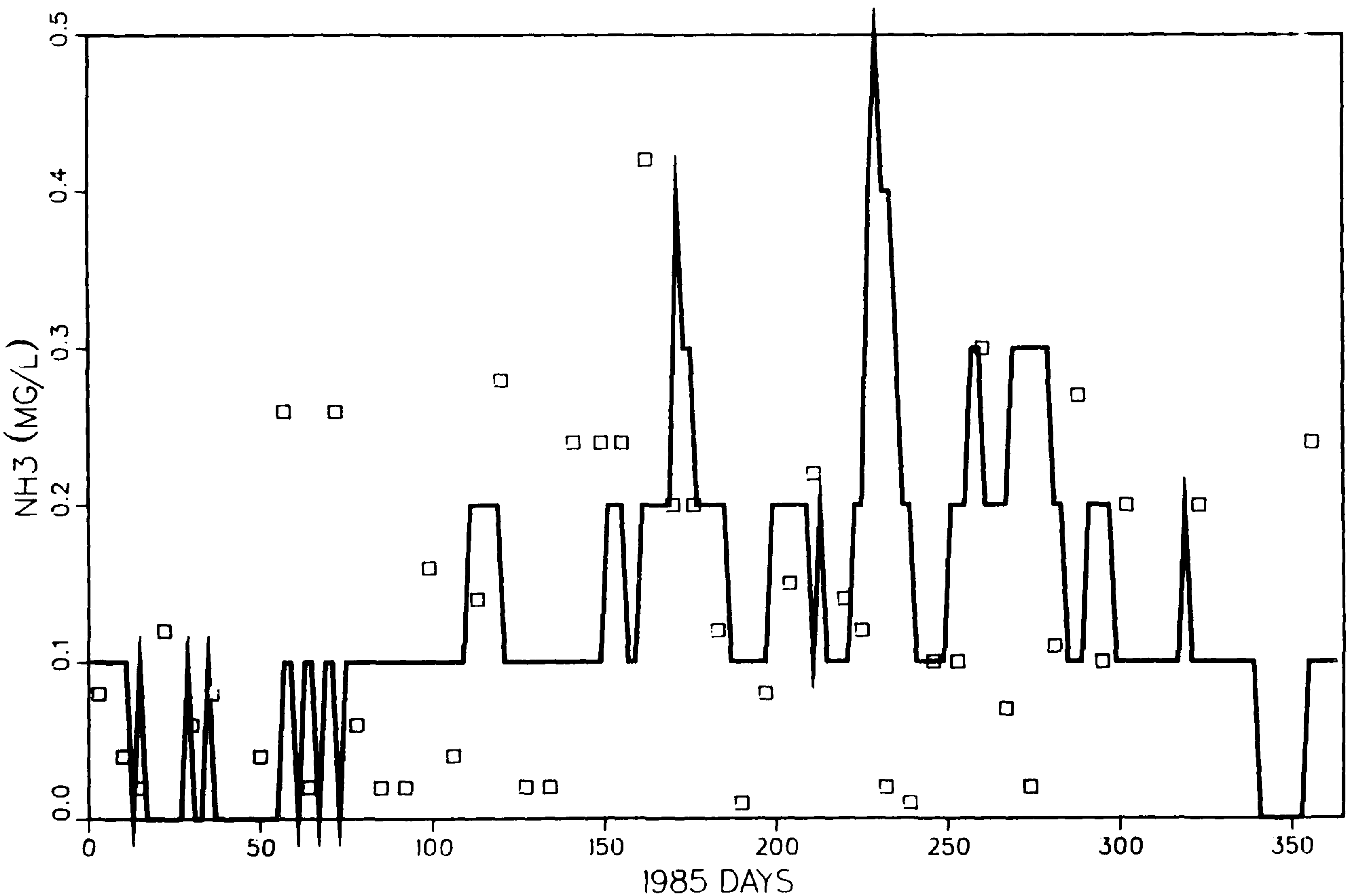


Figure AI-29

AMMONIA COMPARISON
CHEATHAM RESERVOIR
@ CLEES FERRY

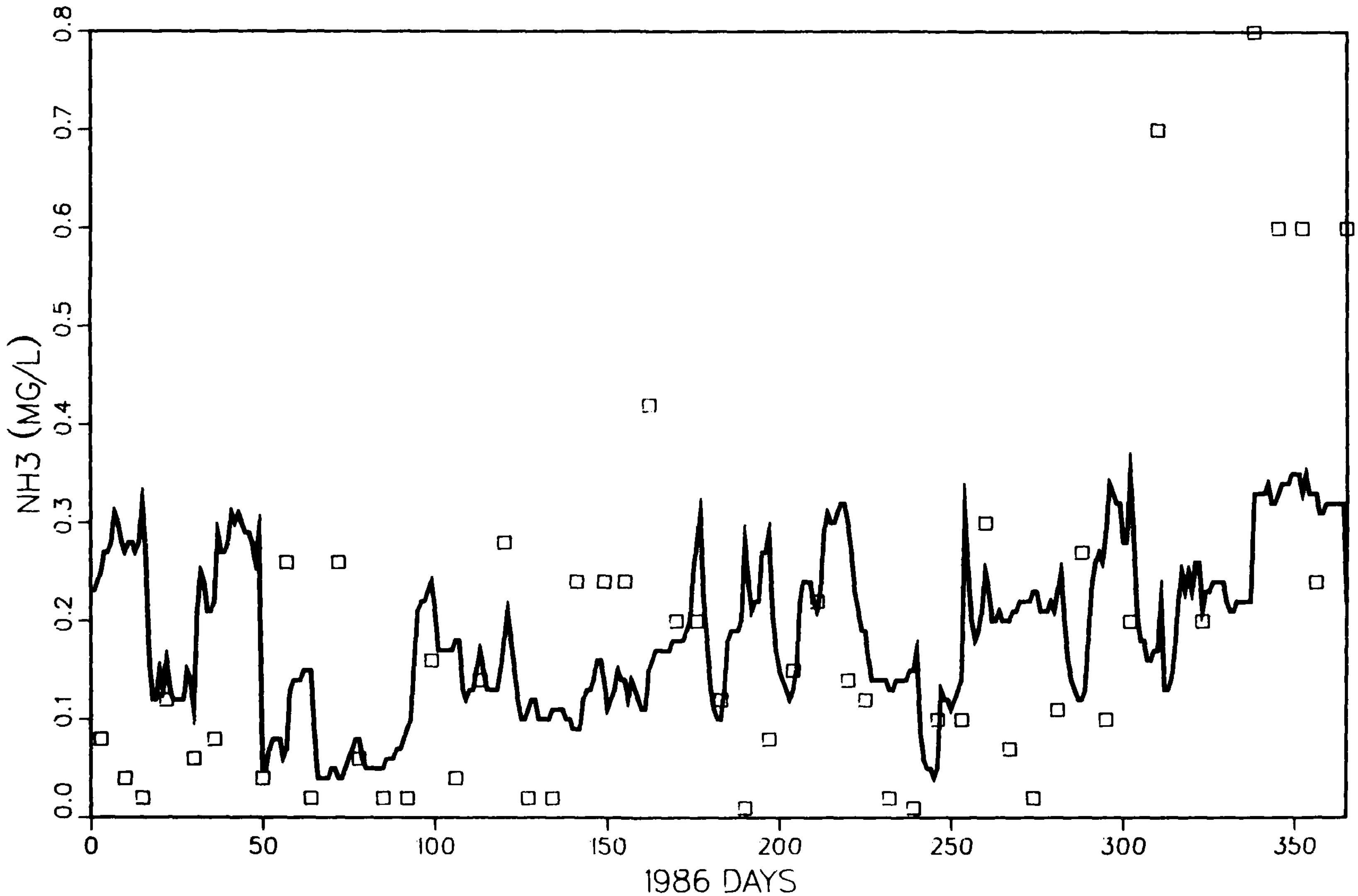
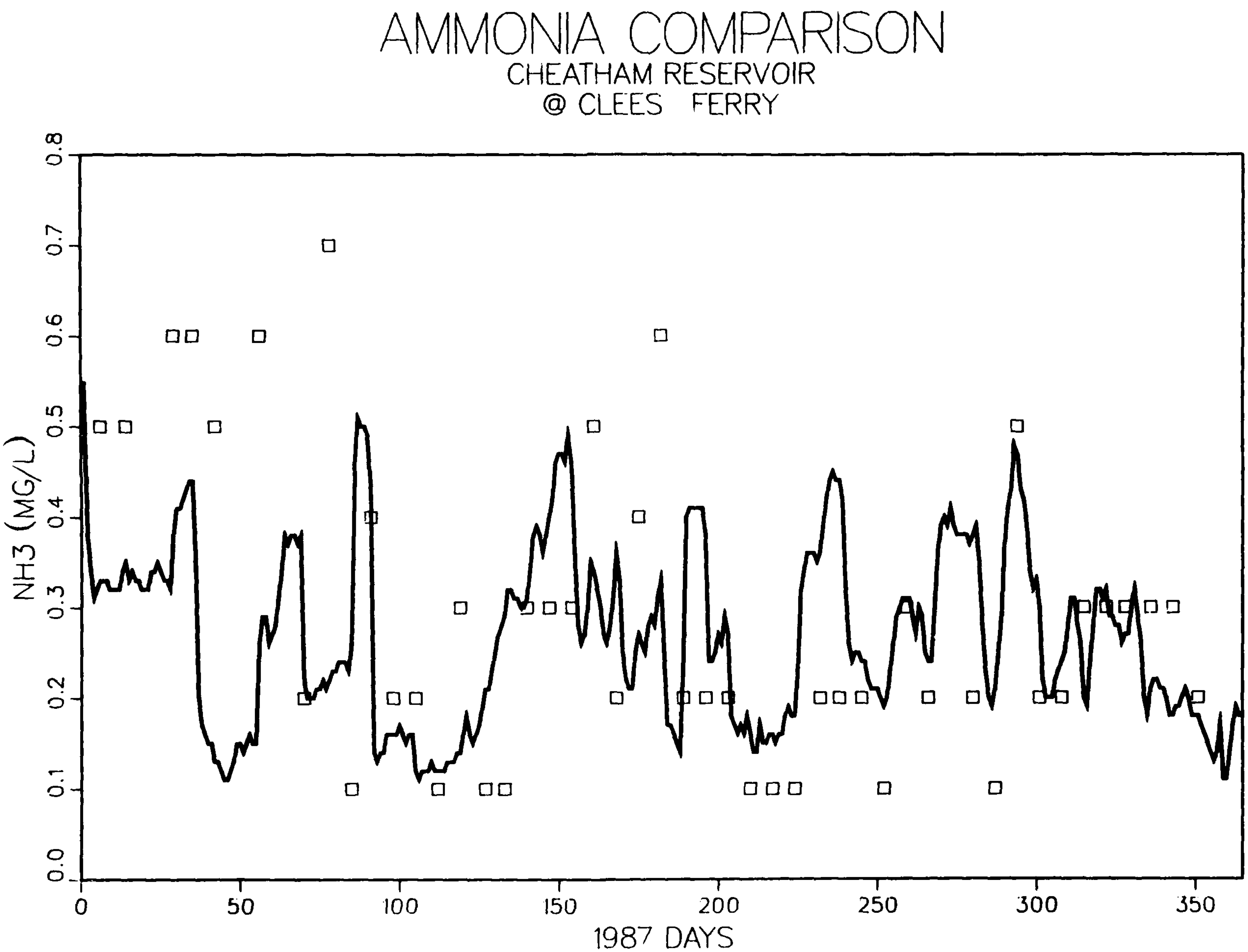


Figure AI-30


AMMONIA COMPARISON
CHEATHAM RESERVOIR
@ CLEES FERRY
NH3 (MG/L)
0.0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0
50
100
150
200
250
300
350
1987 DAYS

Figures AI 31-33. These figures simply show that the Metro river run data were used as input to the BETTER model for the total phosphorus parameter.

Figure 31

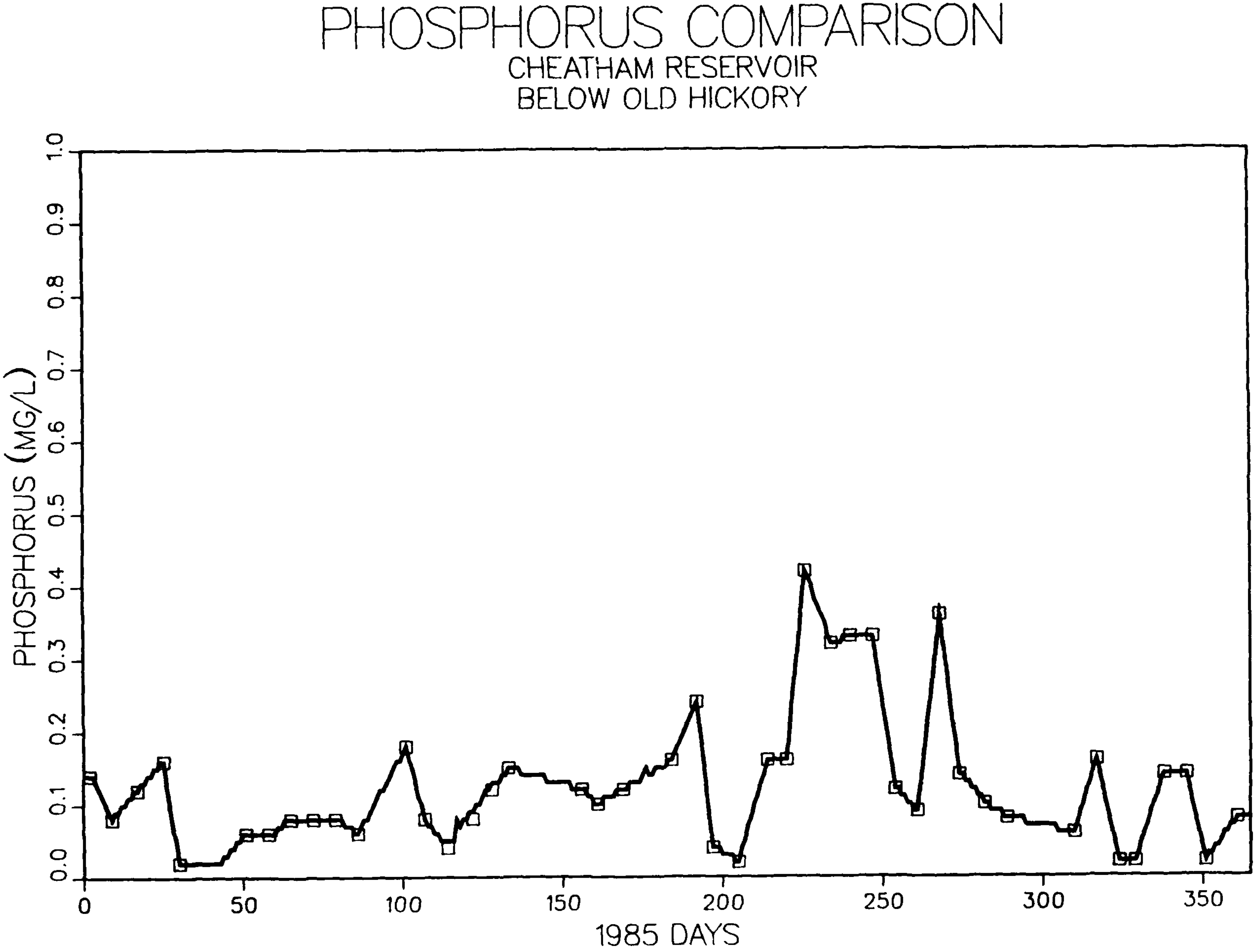

PHOSPHORUS COMPARISON
CHEATHAM RESERVOIR
BELOW OLD HICKORY
PHOSPHORUS (MG/L)
0.0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1.0
0
50
100
150
200
250
300
350
1985 DAYS

Figure AI-32

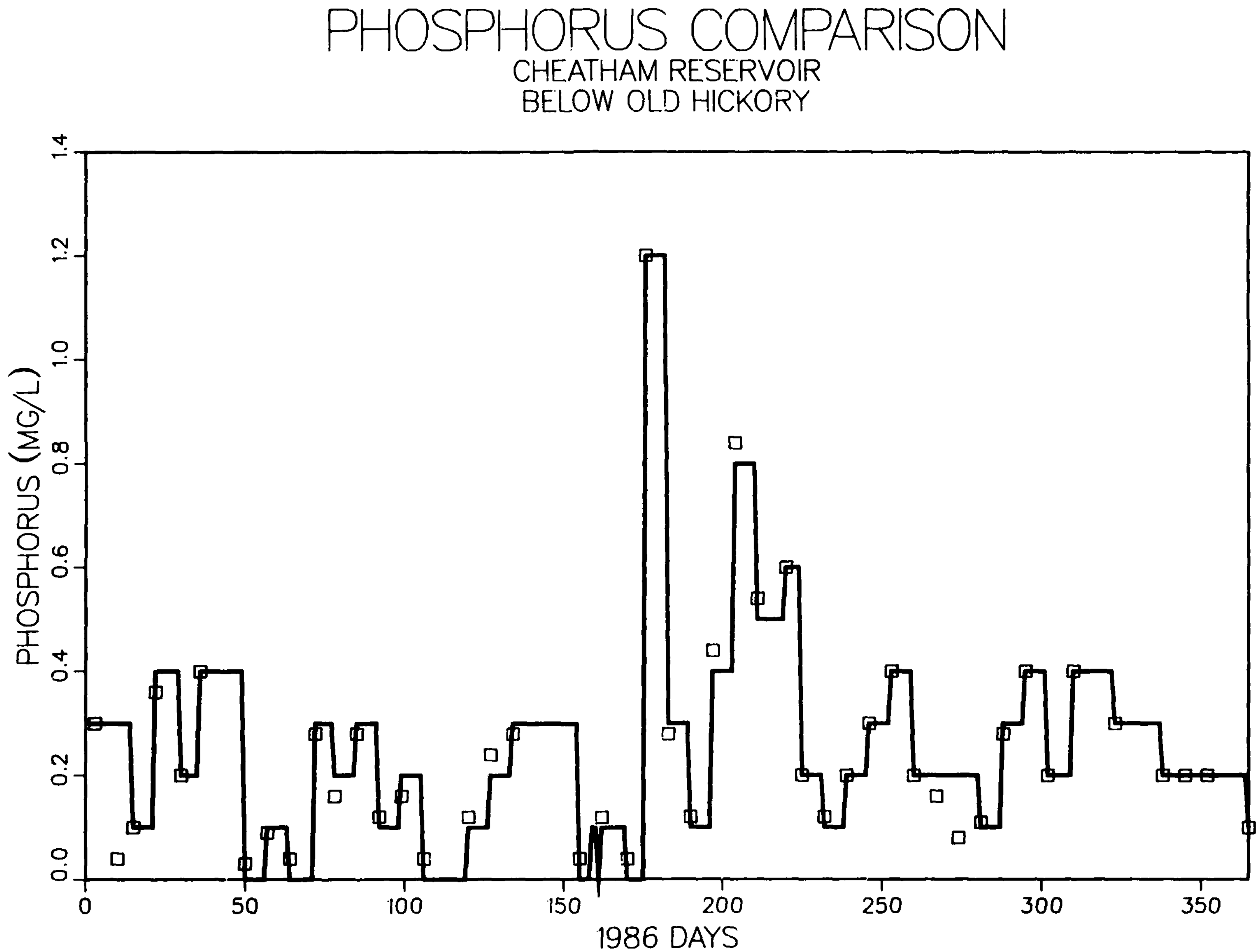
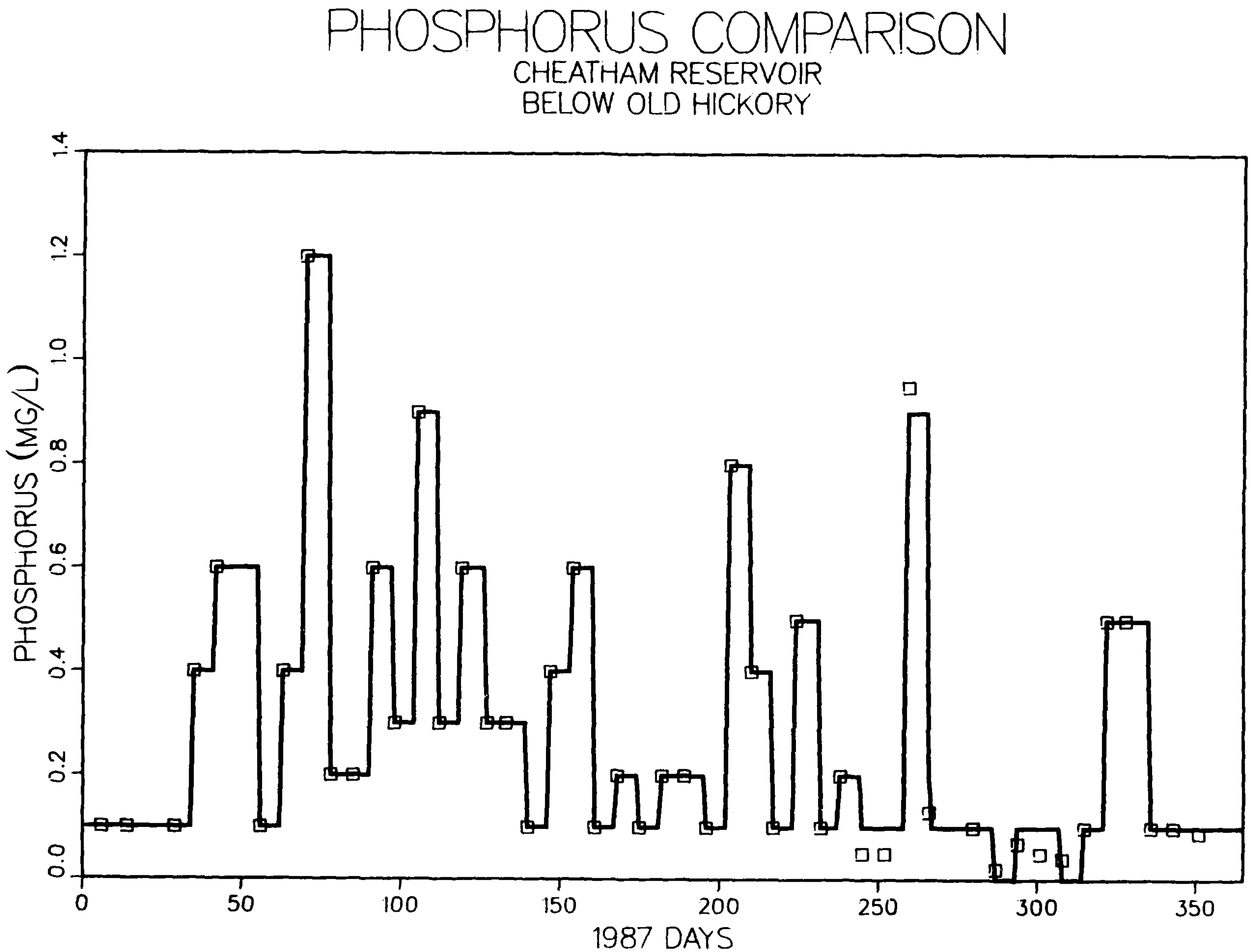

PHOSPHORUS COMPARISON
CHEATHAM RESERVOIR
BELOW OLD HICKORY
PHOSPHORUS (MG/L)
0.0
0.2
0.4
0.6
0.8
1.0
1.2
1.4
0
50
100
150
200
250
300
350
1986 DAYS

Figure AI-33


PHOSPHORUS COMPARISON
CHEATHAM RESERVOIR
BELOW OLD HICKORY
PHOSPHORUS (MG/L)
0.0
0.2
0.4
0.6
0.8
1.0
1.2
1.4
0
50
100
150
200
250
300
350
1987 DAYS

<u>Figures AI 34-36</u>. These three figures show the relationship between total phosphorus as predicted by BETTER and field data collected by Metro river runs at Clees Ferry. For 1985, correlation was good while for 1986 it was very poor and for 1987 it was poor. There was so much variation that the means were all statistically similar. However, visual analysis of these figures shows that the model usually over predicts total phosphorus by a few tenths. This is probably due to a lack of digestion in the total phosphorus test.

Year	R-value	Difference in Means	Prob >T
1985	0.667	0.000681 mg/l	0.0832
1986	0.089	0.00717	0.2312
1987	0.244	0.000889	0.2527

Figure AI-34

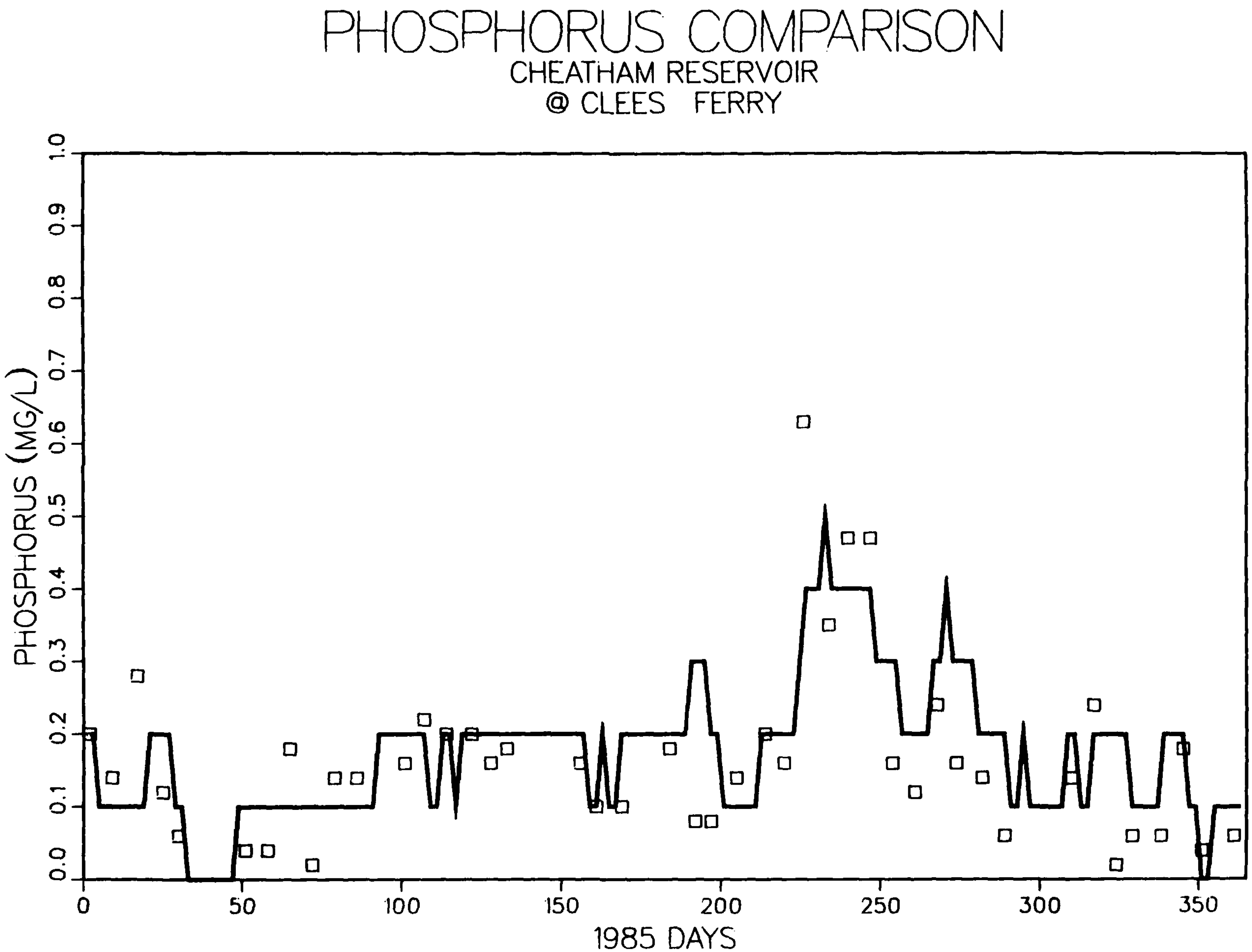

PHOSPHORUS COMPARISON
CHEATHAM RESERVOIR
@ CLEES FERRY
PHOSPHORUS (MG/L)
0.0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1.0
0
50
100
150
200
250
300
350
1985 DAYS

Figure AI-35

PHOSPHORUS COMPARISON
CHEATHAM RESERVOIR
@ CLEES FERRY

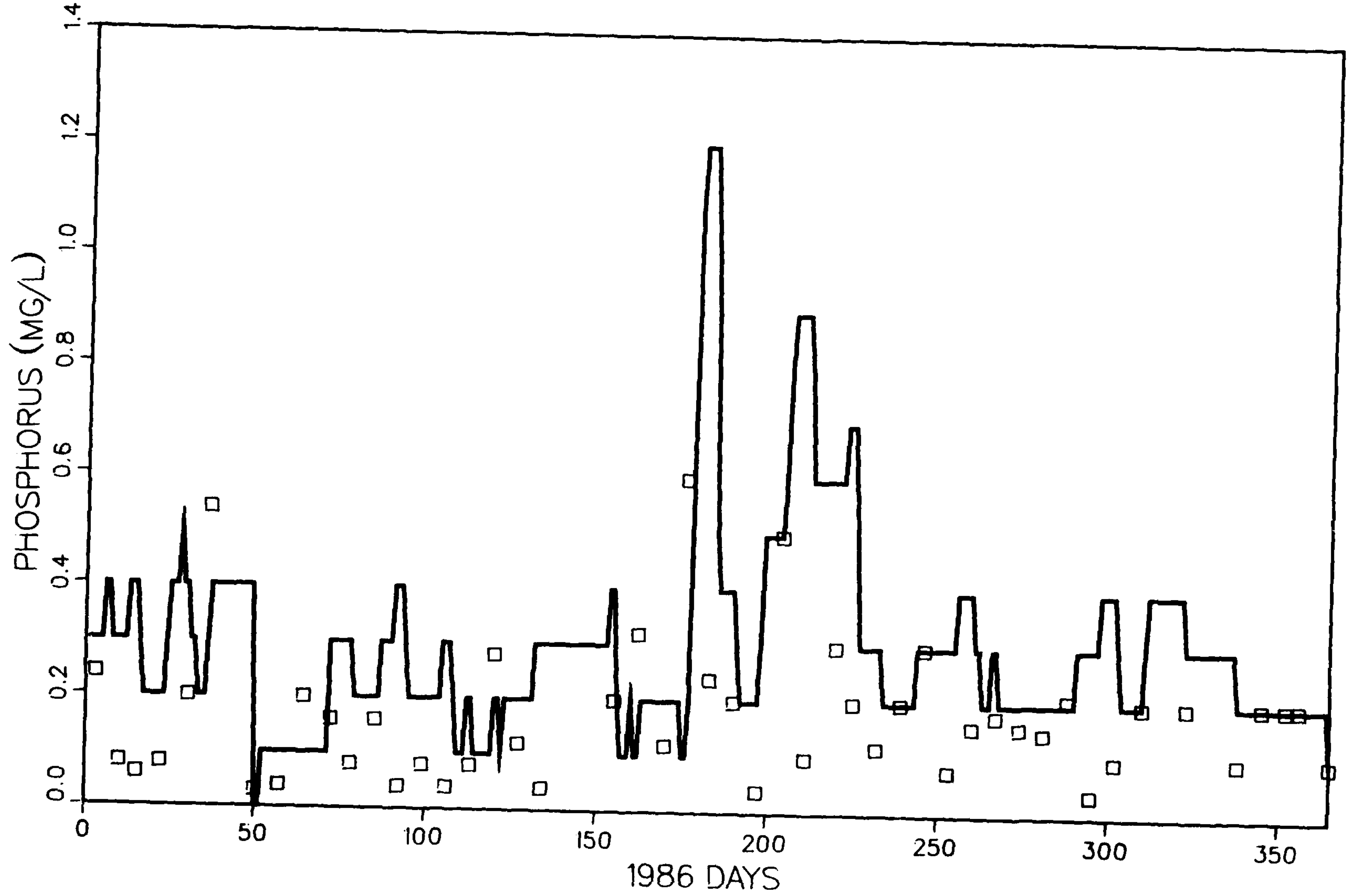
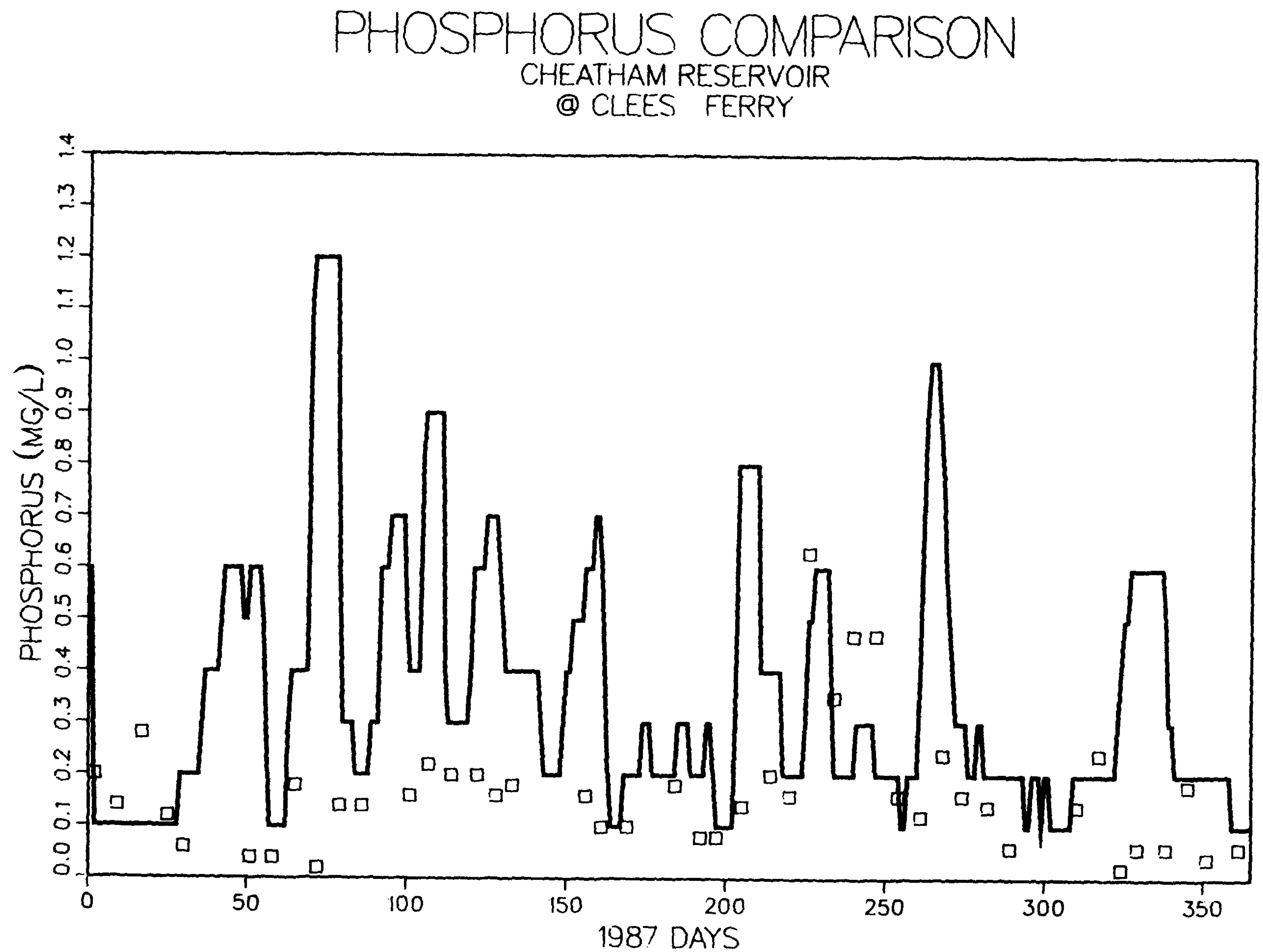


Figure AI-36



PHOSPHORUS COMPARISON
CHEATHAM RESERVOIR
@ CLEES FERRY
PHOSPHORUS (MG/L)
0.0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1.0
1.1
1.2
1.3
1.4
0
50
100
150
200
250
300
350
1987 DAYS

Figures AI 37-39 - These figures show BOD relationships between the BETTER predictions and Metro river run data at Old Hickory. The BETTER model does not include an actual BOD decay algorithm, but simulates BOD indirectly using dissolved organic matter and detritus. The output BOD_5 is at 20°C as is the field BOD. The correlation coefficients for 1985, 1986 and 1987 were 0.962, 0.955, and 0.988 respectively.

Figure AI-37

BOD COMPARISON
CHEATHAM RESERVOIR
BELOW OLD HICKORY

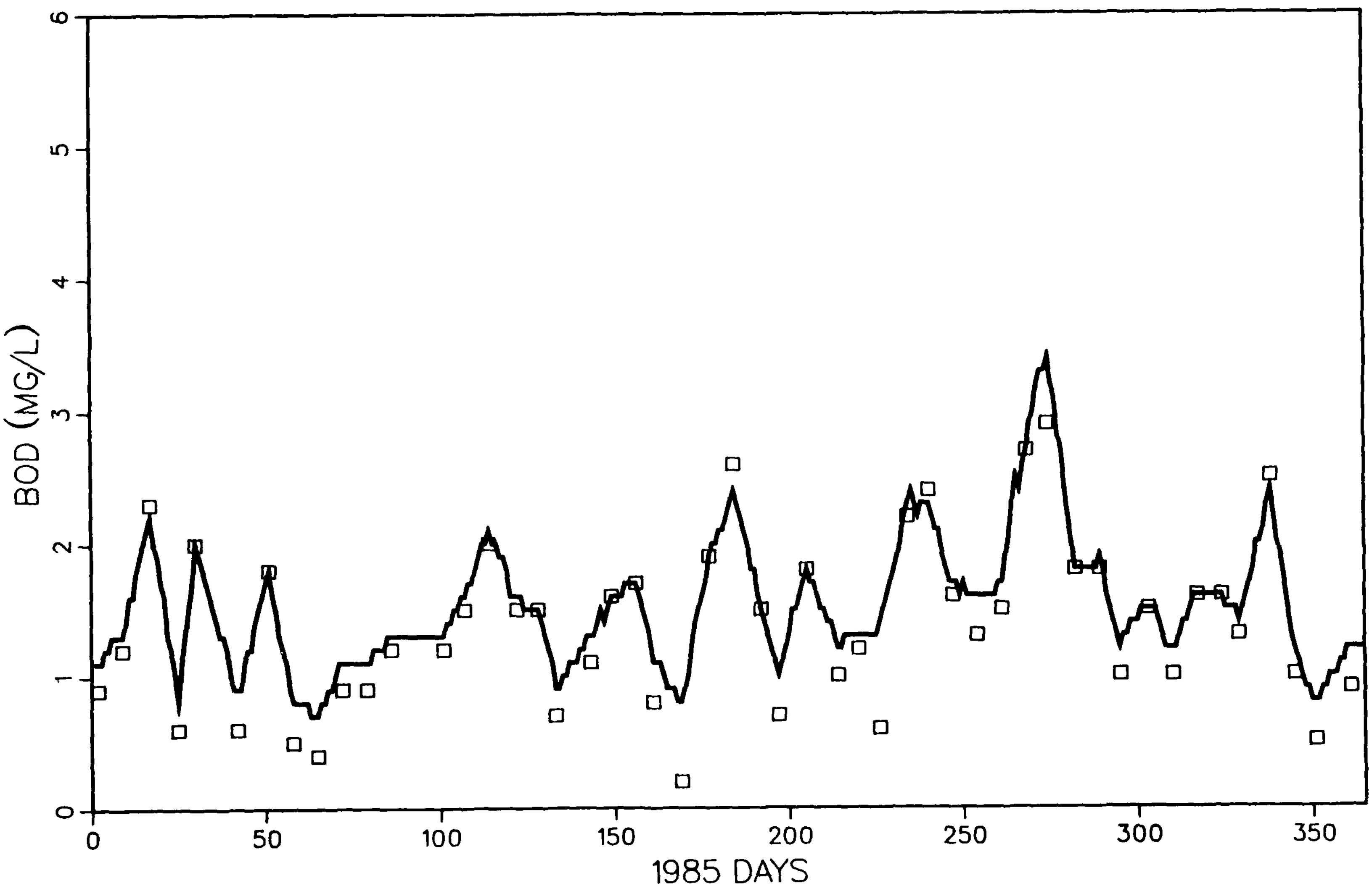


Figure AI-38

BOD COMPARISON
CHEATHAM RESERVOIR
BELOW OLD HICKORY

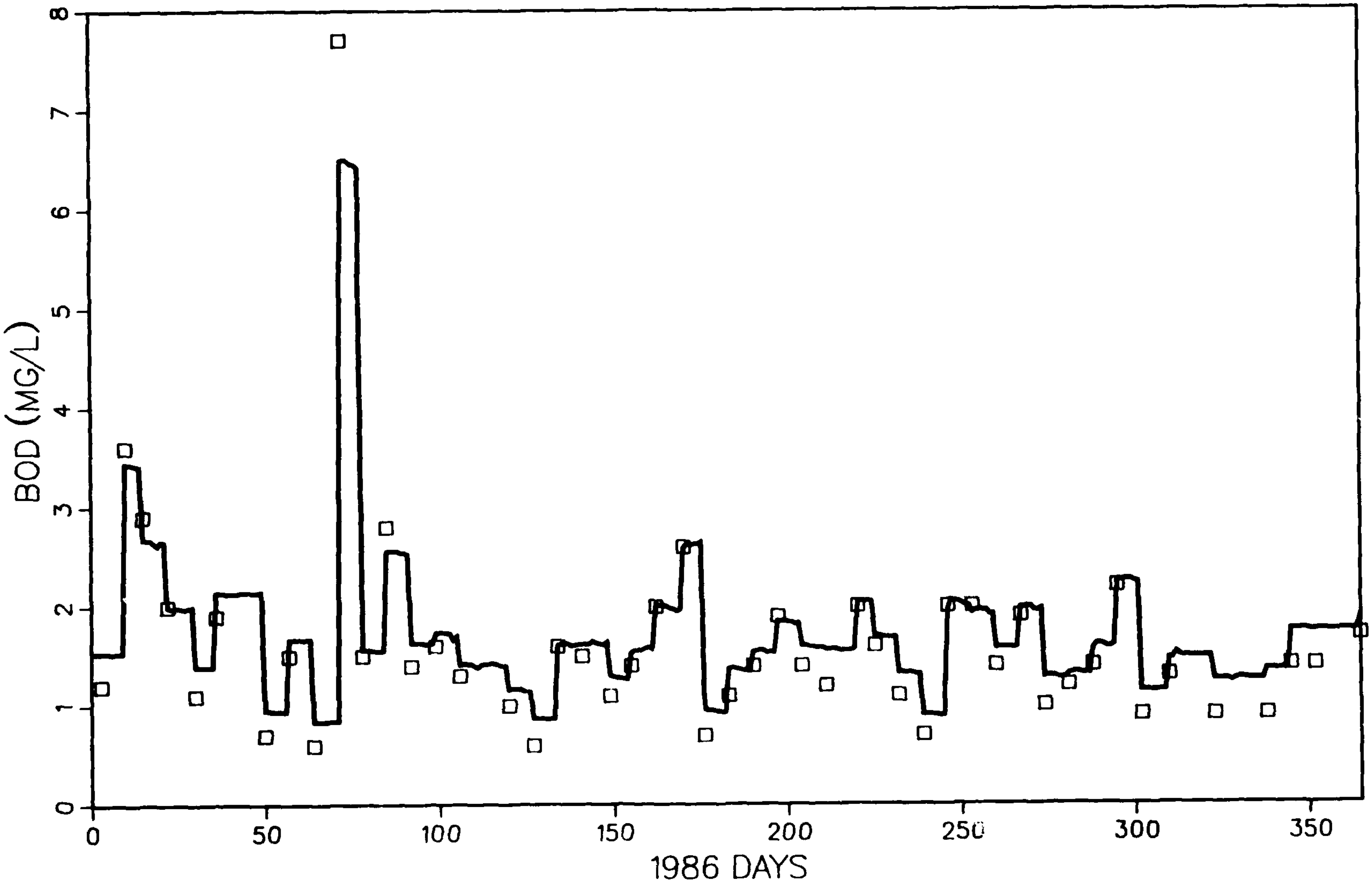
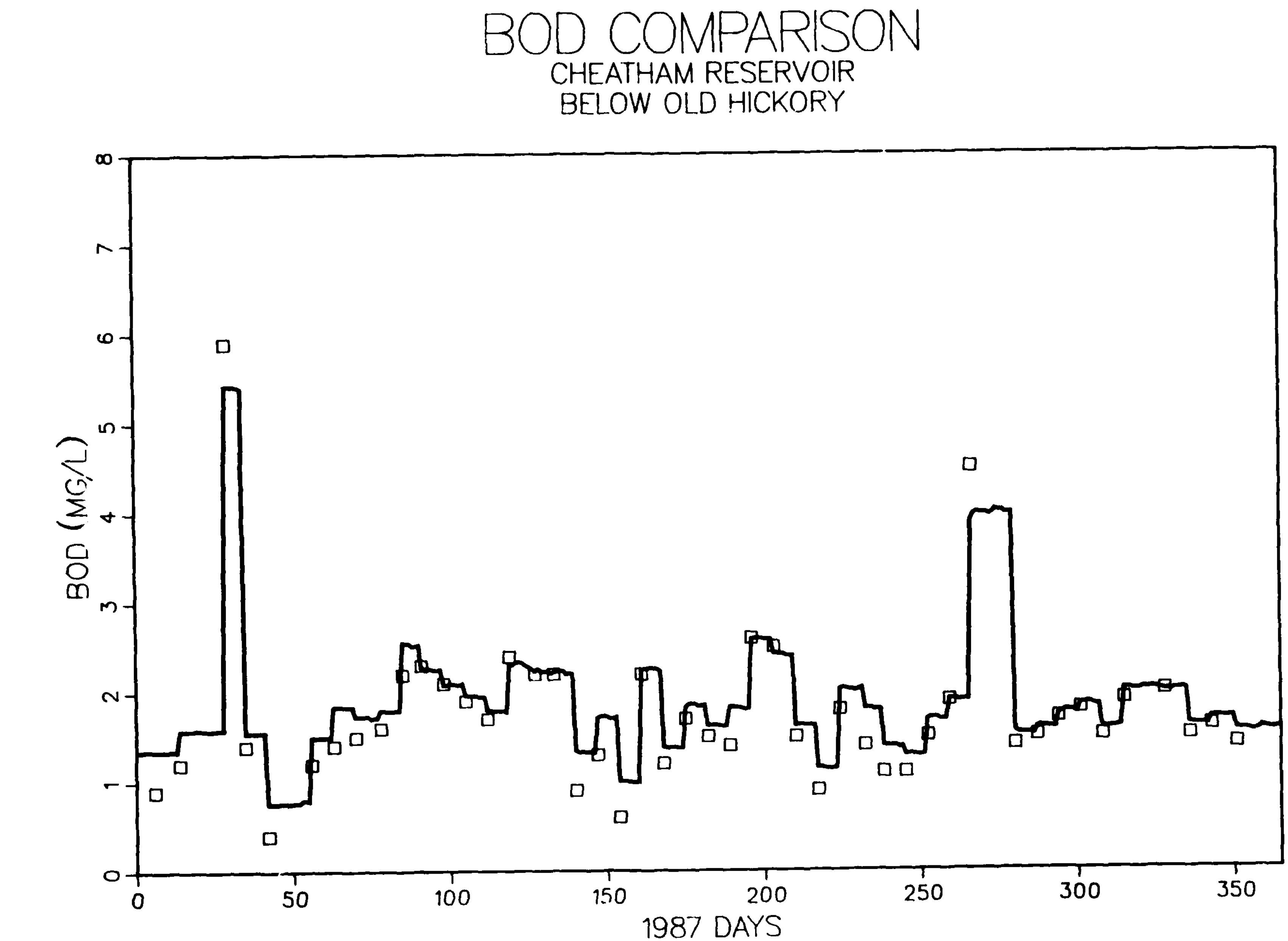


Figure AI-39


BOD COMPARISON
CHEATHAM RESERVOIR
BELOW OLD HICKORY
BOD (MG/L)
0
1
2
3
4
5
6
7
8
0
50
100
150
200
250
300
350
1987 DAYS

Figures AI 40-42 - These three figures show the relationship between BOD as predicted by BETTER and field/laboratory data collected by Metro river runs at Clees Ferry. The linear correlations were fair for each year. The mean values of each group were statistically identical. Since the accuracy of the BOD test is only about 20%, examination of these figures shows BOD to be nicely modeled.

Year	R-value	Difference in Means	Prob > T
1985	0.476	0.172	0.1256
1986	0.301	-0.088	0.5146
1987	0.433	-0.174	0.1776

Figure AI-40

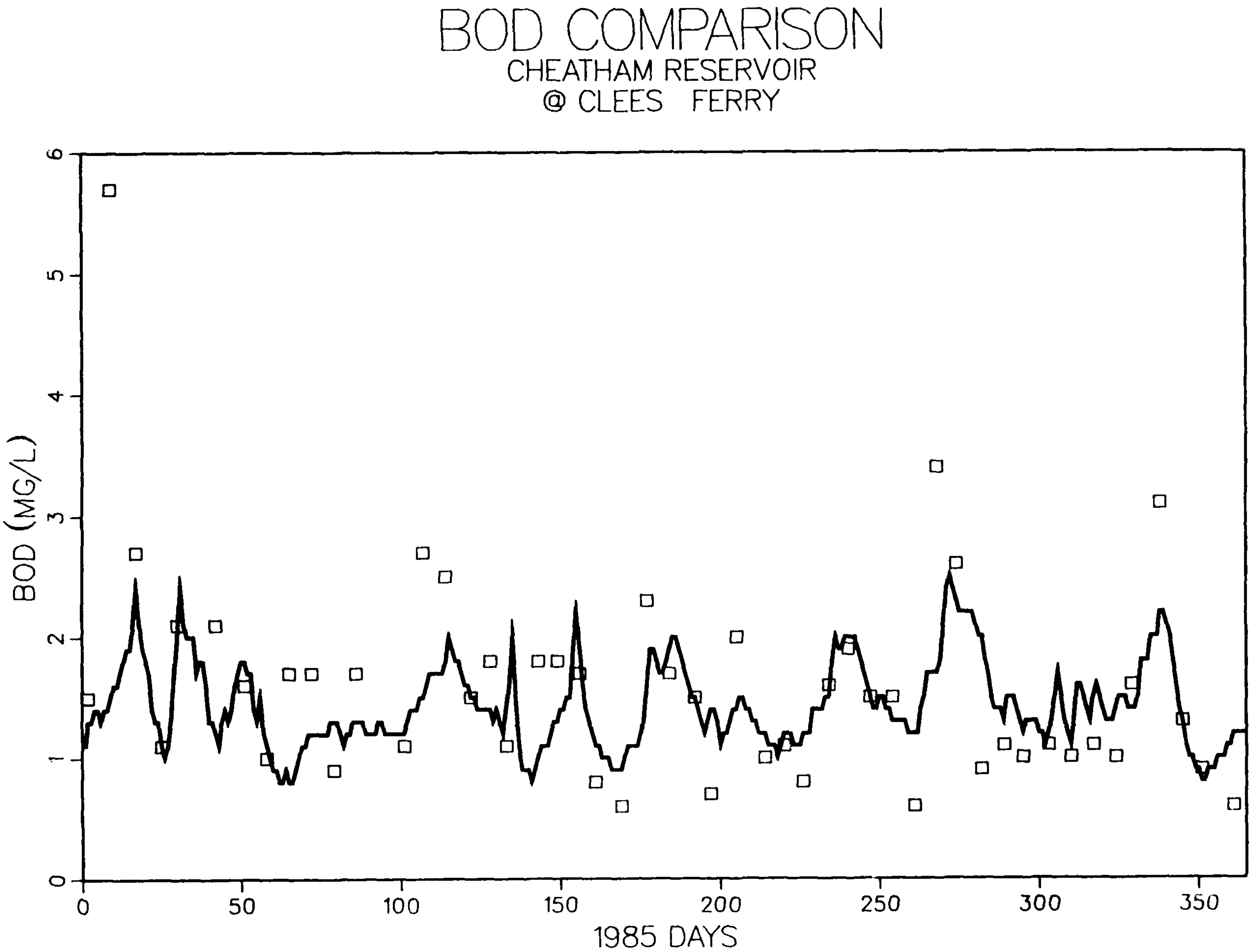

BOD COMPARISON
CHEATHAM RESERVOIR
@ CLEES FERRY
BOD (MG/L)
0
1
2
3
4
5
6
0
50
100
150
200
250
300
350
1985 DAYS

Figure AI-41

BOD COMPARISON

CHEATHAM RESERVOIR
@ CLEES FERRY

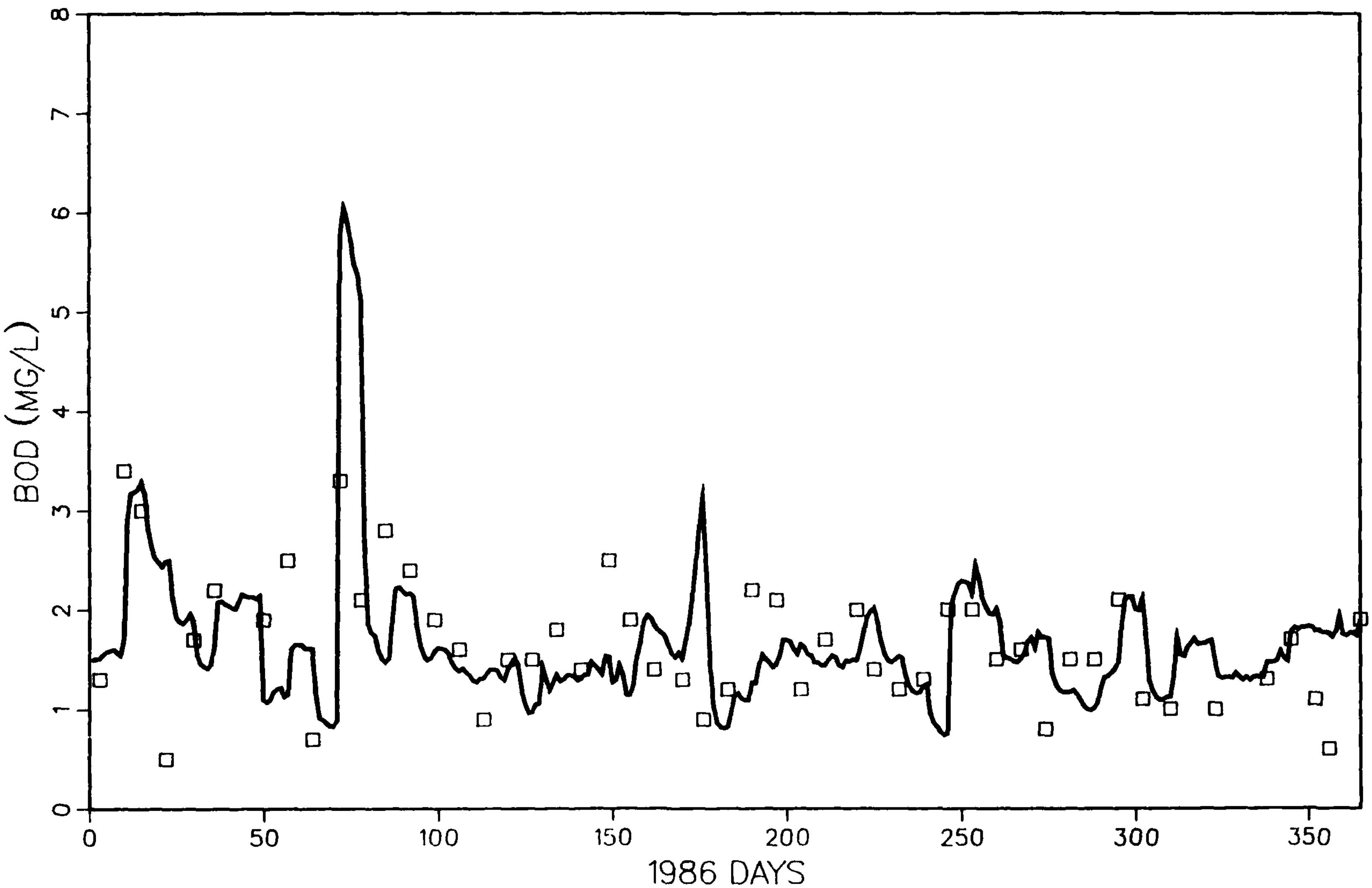
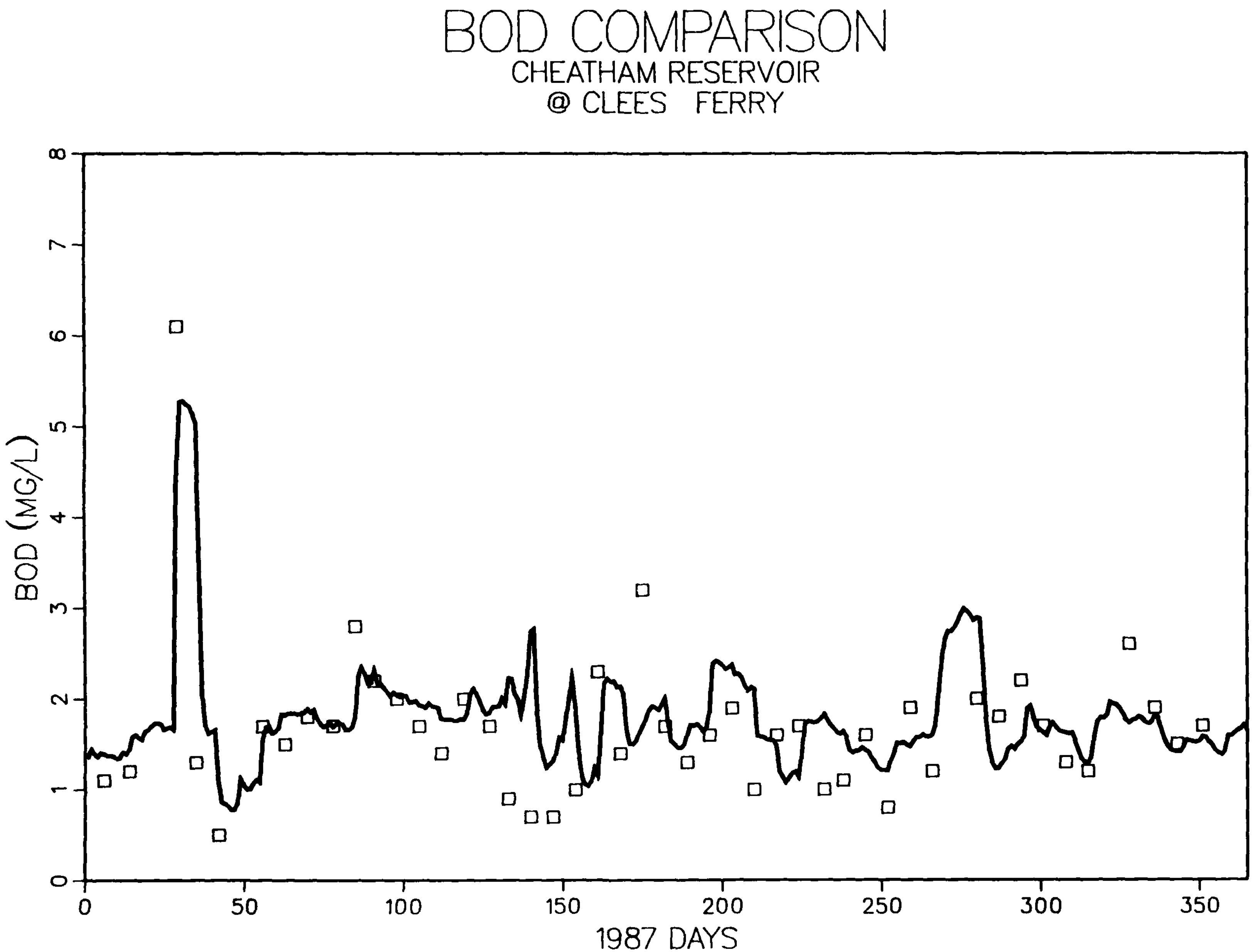


Figure AI-42



BOD COMPARISON
CHEATHAM RESERVOIR
@ CLEES FERRY
BOD (MG/L)
0
1
2
3
4
5
6
7
8
0
50
100
150
200
250
300
350
1987 DAYS

APPENDIX II

Flow and Residence Time Plots for
Cheatham Reservoir from 1959-1987

Figure AII-1

CHEATHAM RESERVOIR 1959

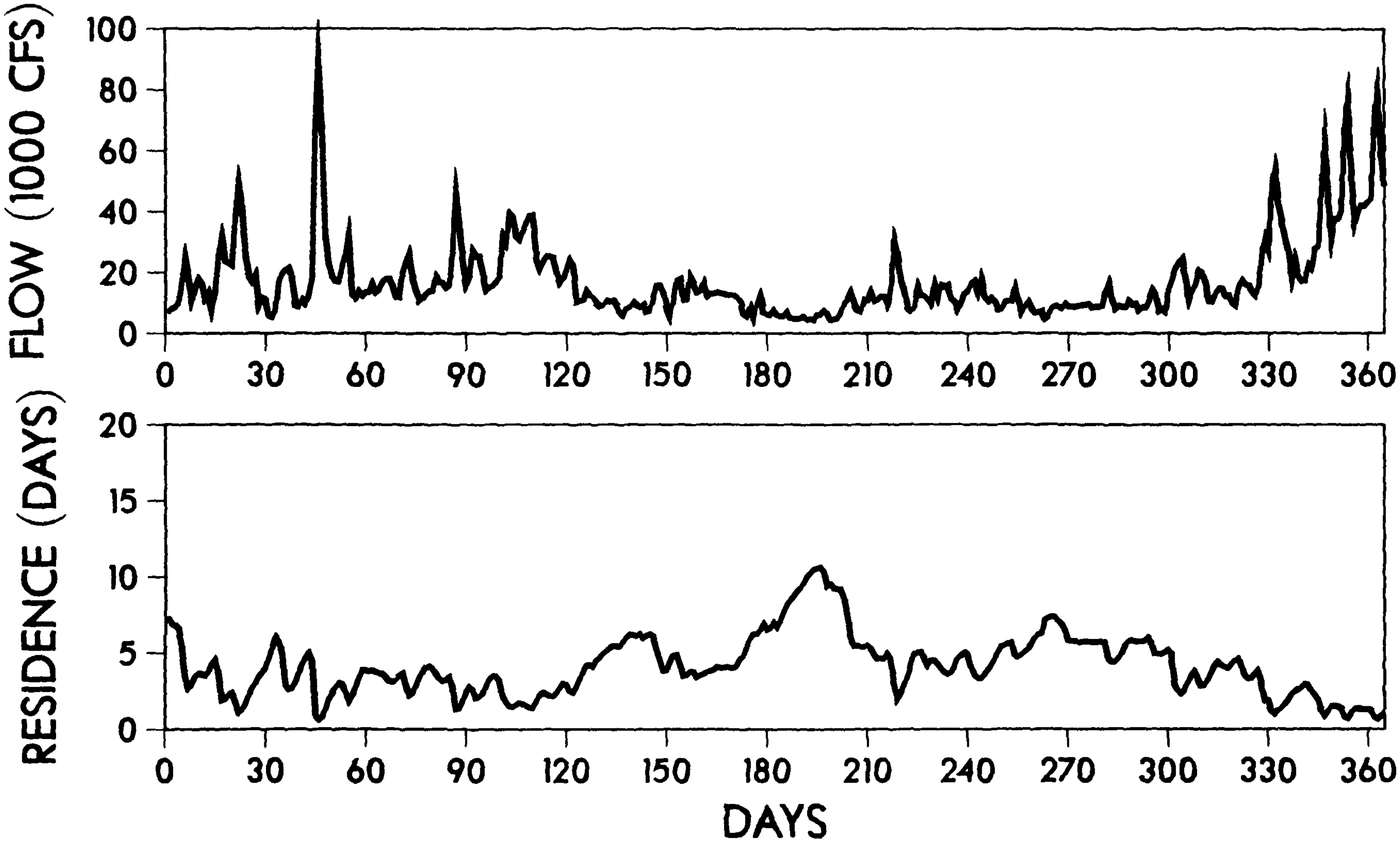


Figure AII-2

CHEATHAM RESERVOIR 1960

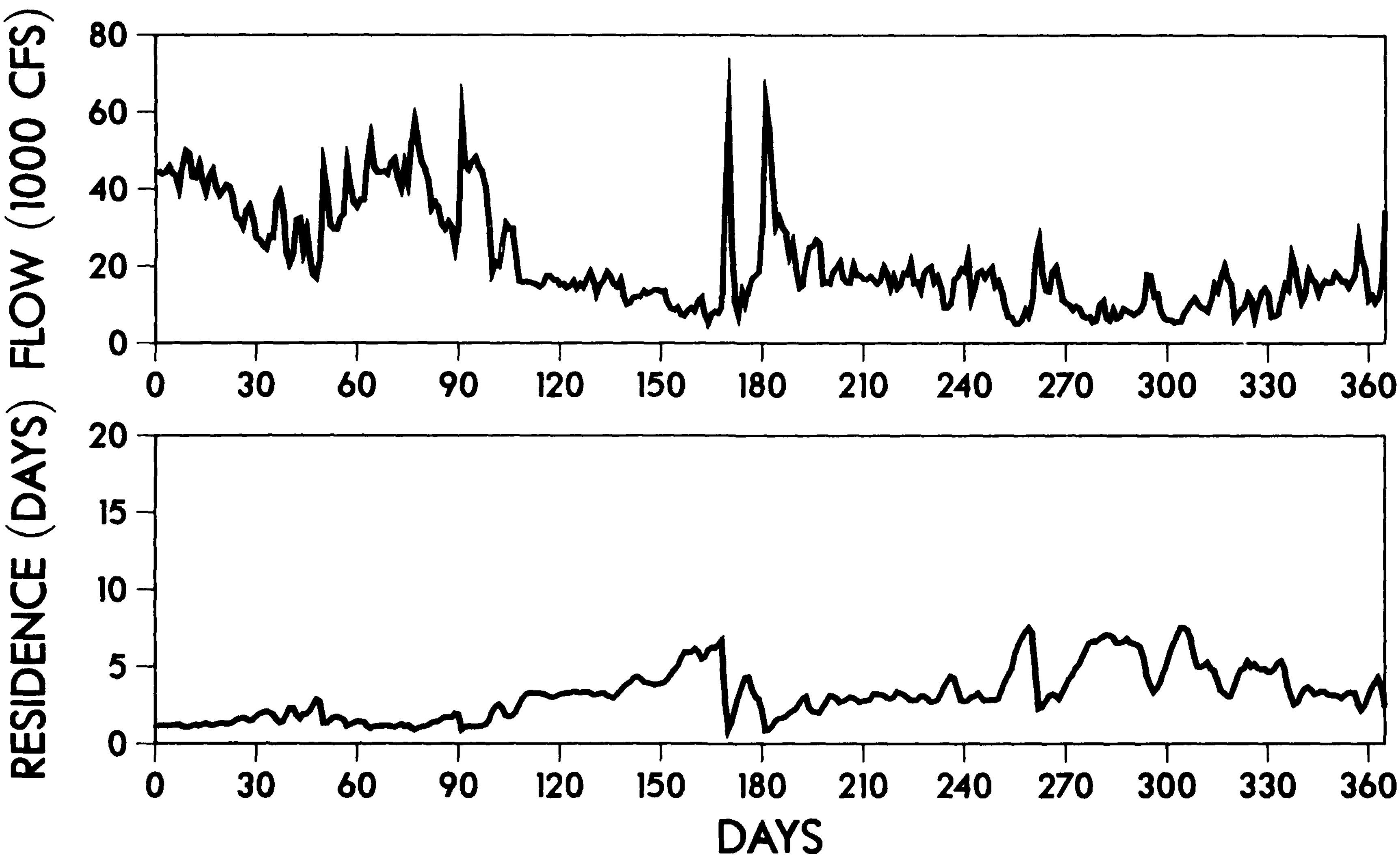


Figure AII-3

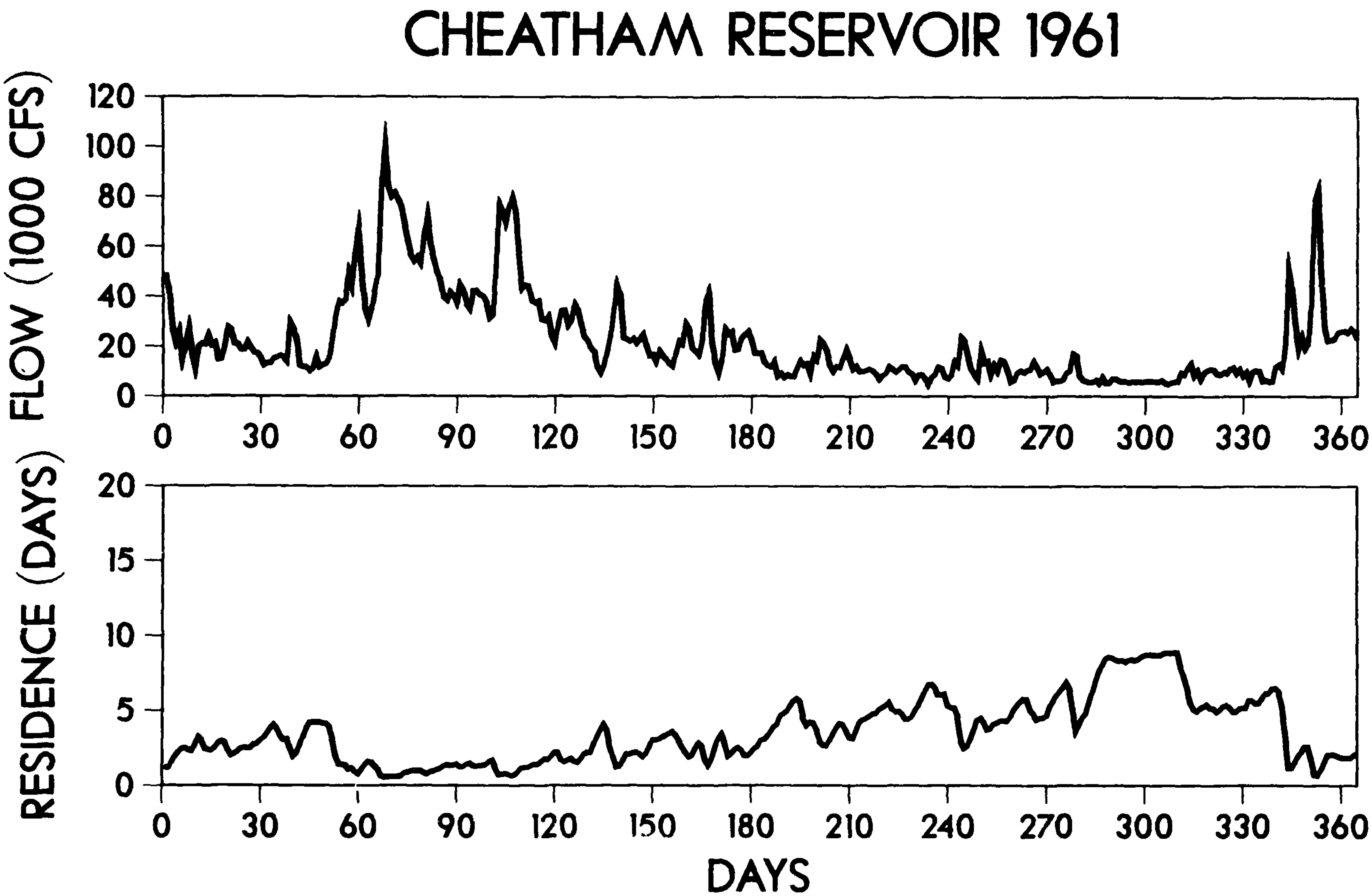
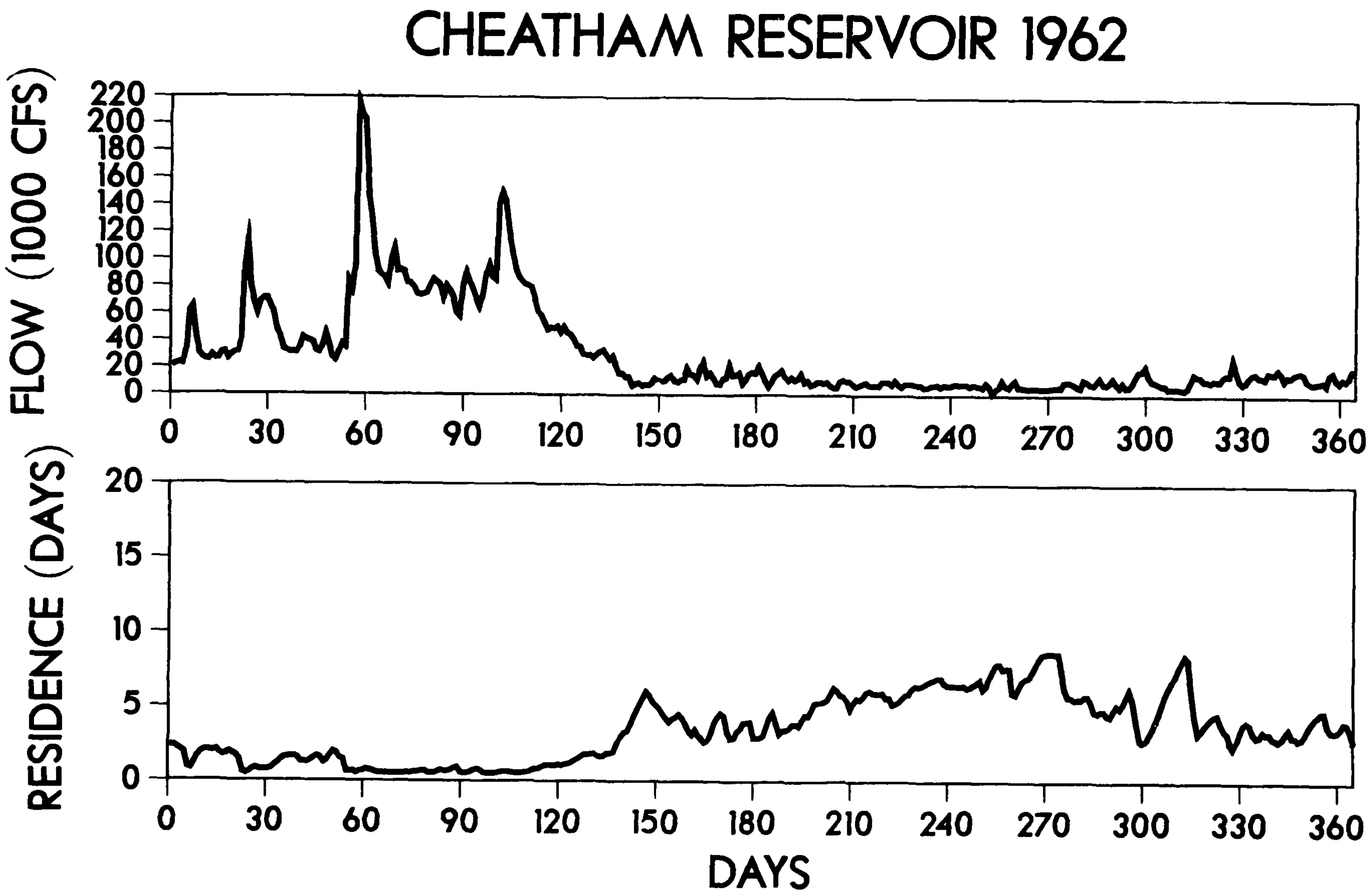

CHEATHAM RESERVOIR 1961
FLOW (1000 CFS)
120
100
80
60
40
20
0
RESIDENCE (DAYS)
20
15
10
5
0
0 30 60 90 120 150 180 210 240 270 300 330 360
DAYS

Figure AII-4



CHEATHAM RESERVOIR 1962
FLOW (1000 CFS)
220
200
180
160
140
120
100
80
60
40
20
0
0
30
60
90
120
150
180
210
240
270
300
330
360
RESIDENCE (DAYS)
20
15
10
5
0
DAYS

Figure AII-5

CHEATHAM RESERVOIR 1963

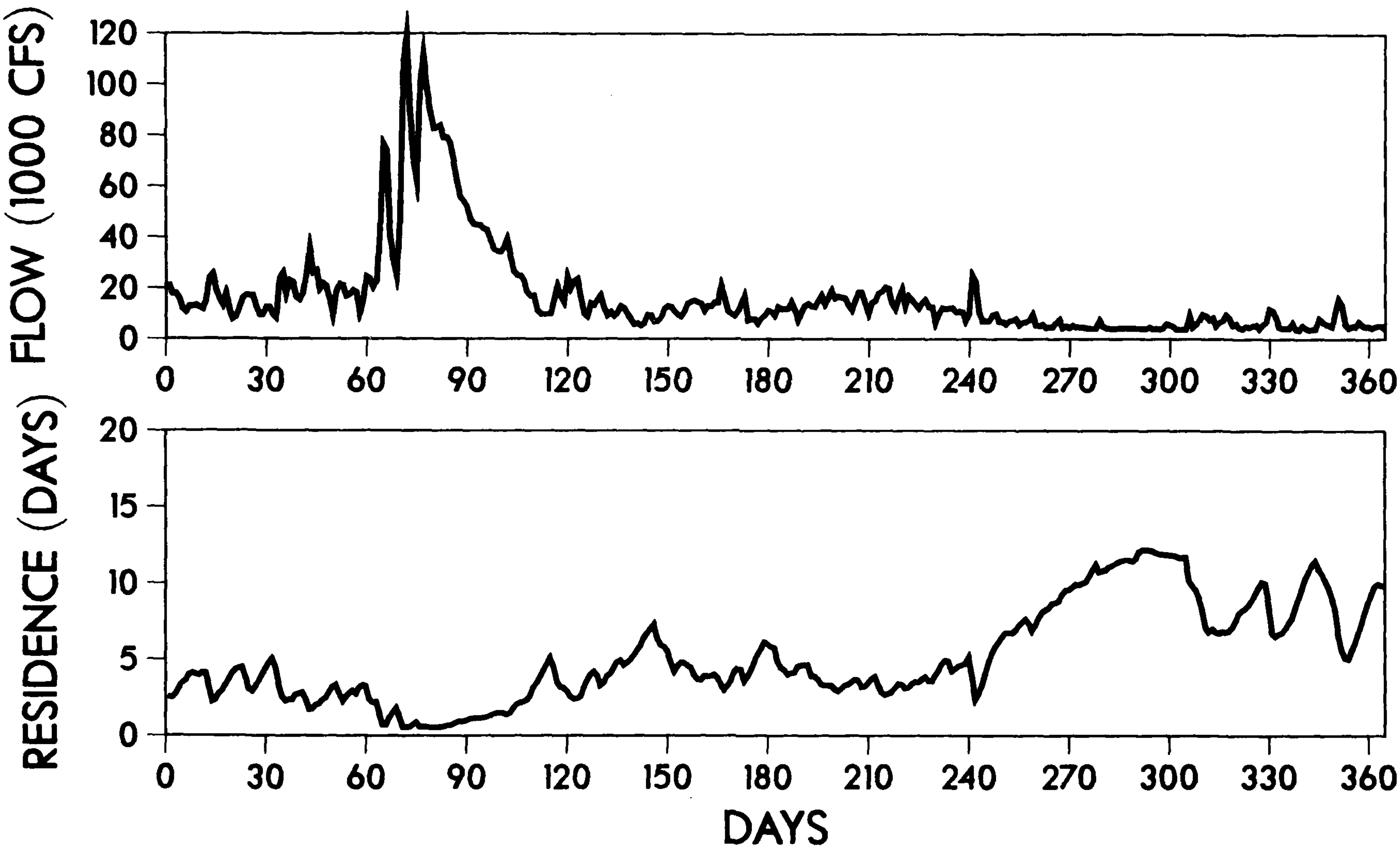


Figure AII-6

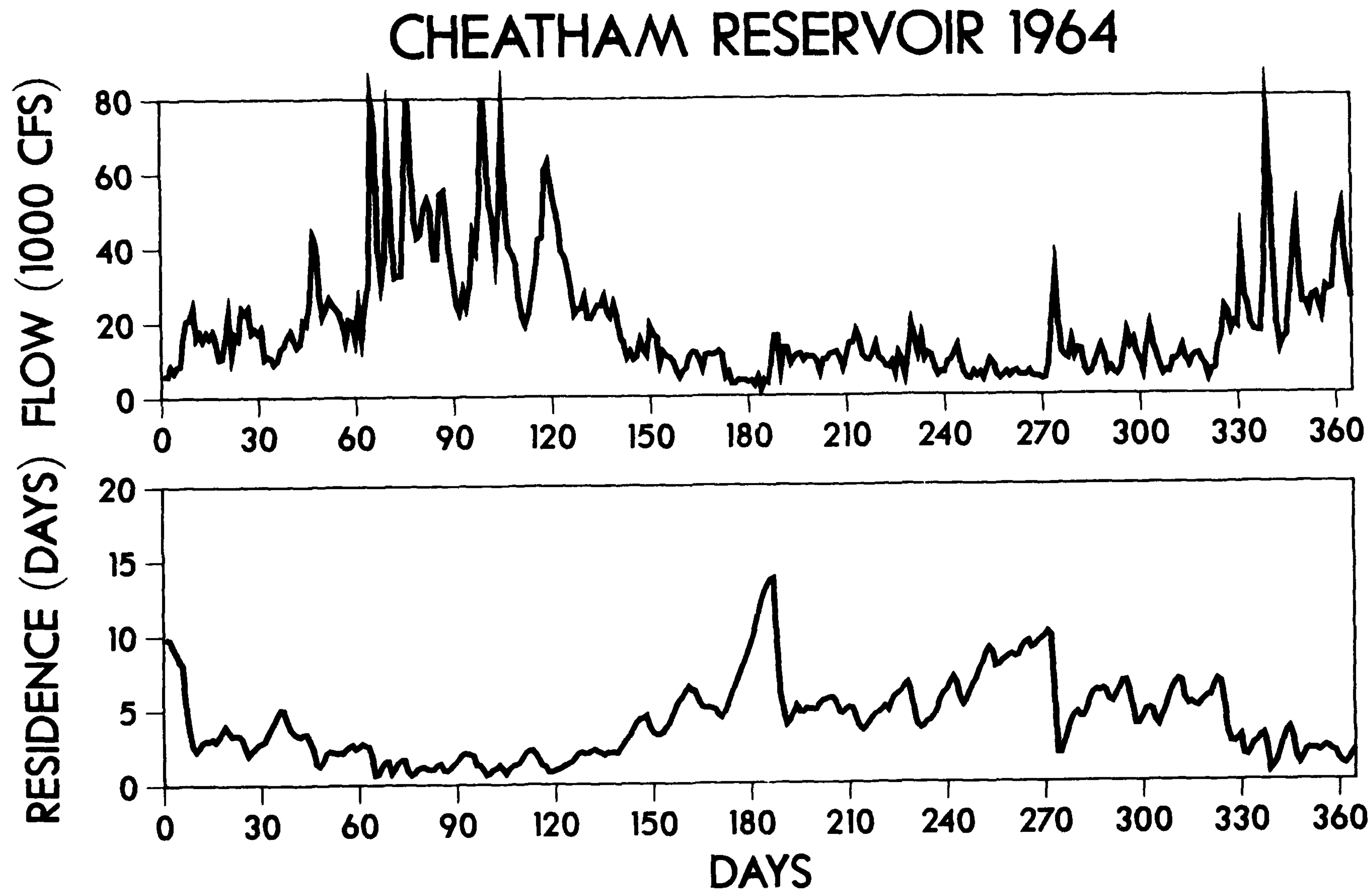

CHEATHAM RESERVOIR 1964
FLOW (1000 CFS)
80
60
40
20
0
0
30
60
90
120
150
180
210
240
270
300
330
360
RESIDENCE (DAYS)
20
15
10
5
0
DAYS

Figure AII-7

CHEATHAM RESERVOIR 1965

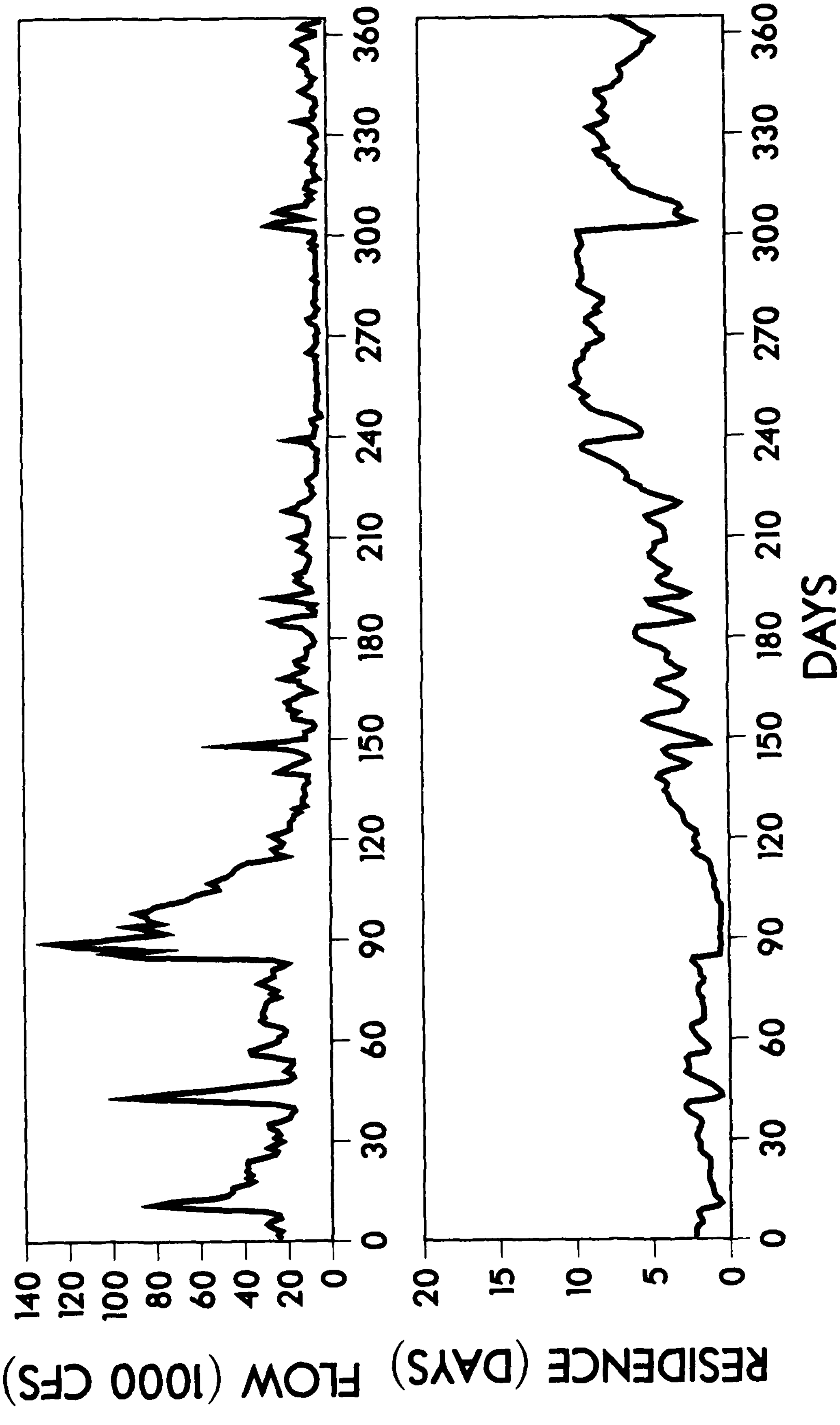


Figure AII-8

CHEATHAM RESERVOIR 1966

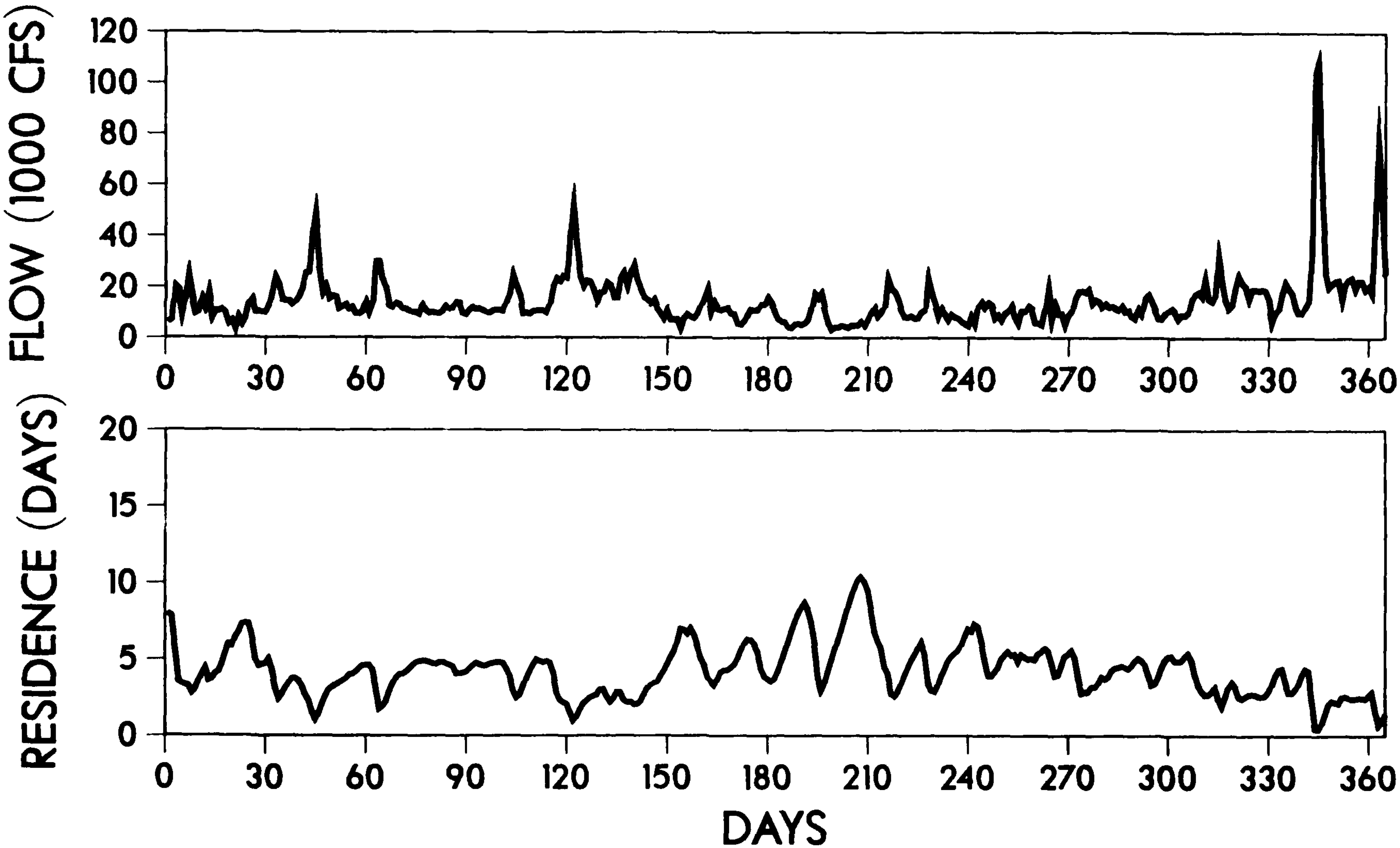


Figure AII-9

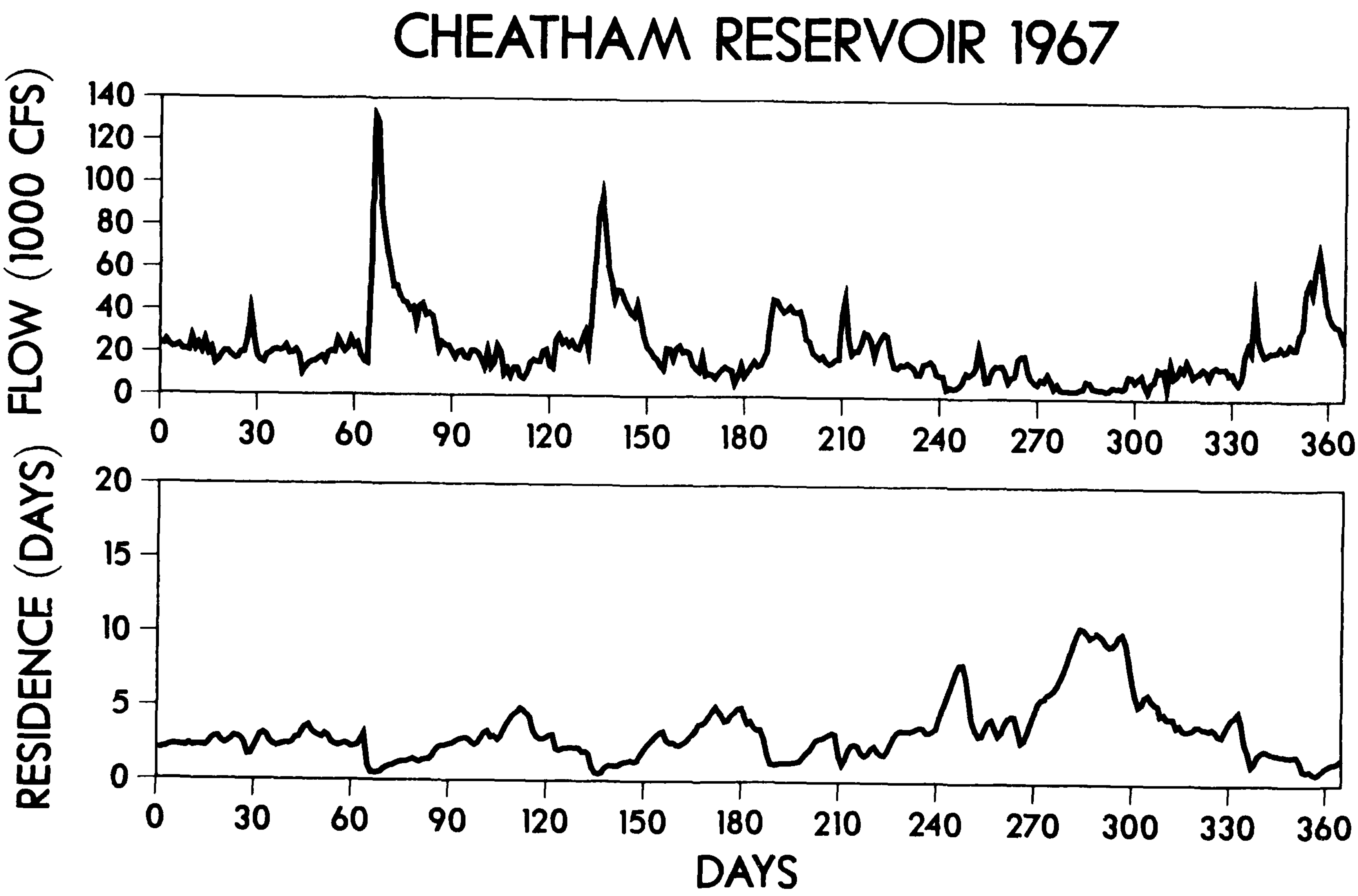

CHEATHAM RESERVOIR 1967
FLOW (1000 CFS)
140
120
100
80
60
40
20
0
RESIDENCE (DAYS)
20
15
10
5
0
0
30
60
90
120
150
180
210
240
270
300
330
360
DAYS

Figure AII-10

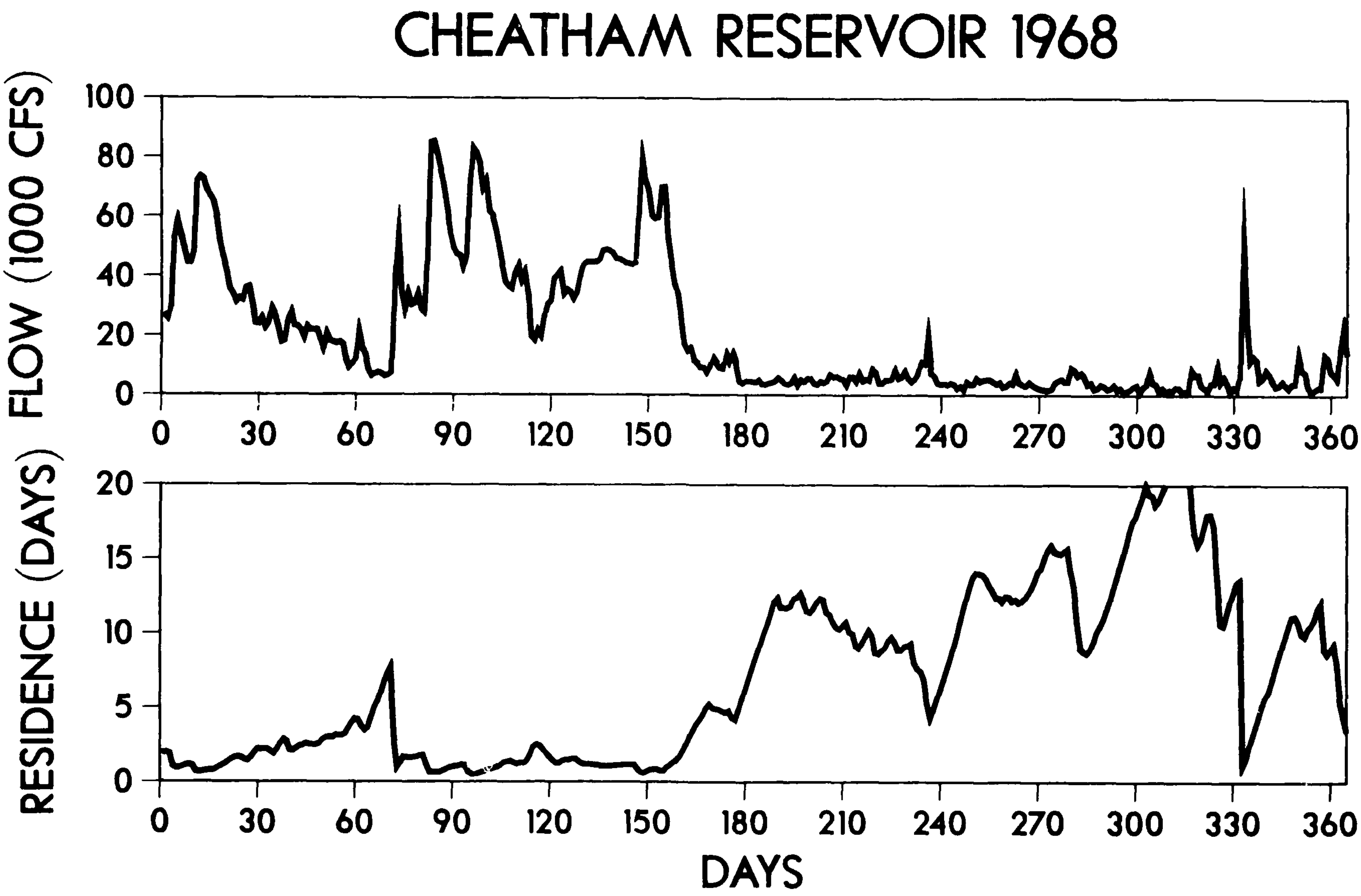


Figure AII-11

CHEATHAM RESERVOIR 1969

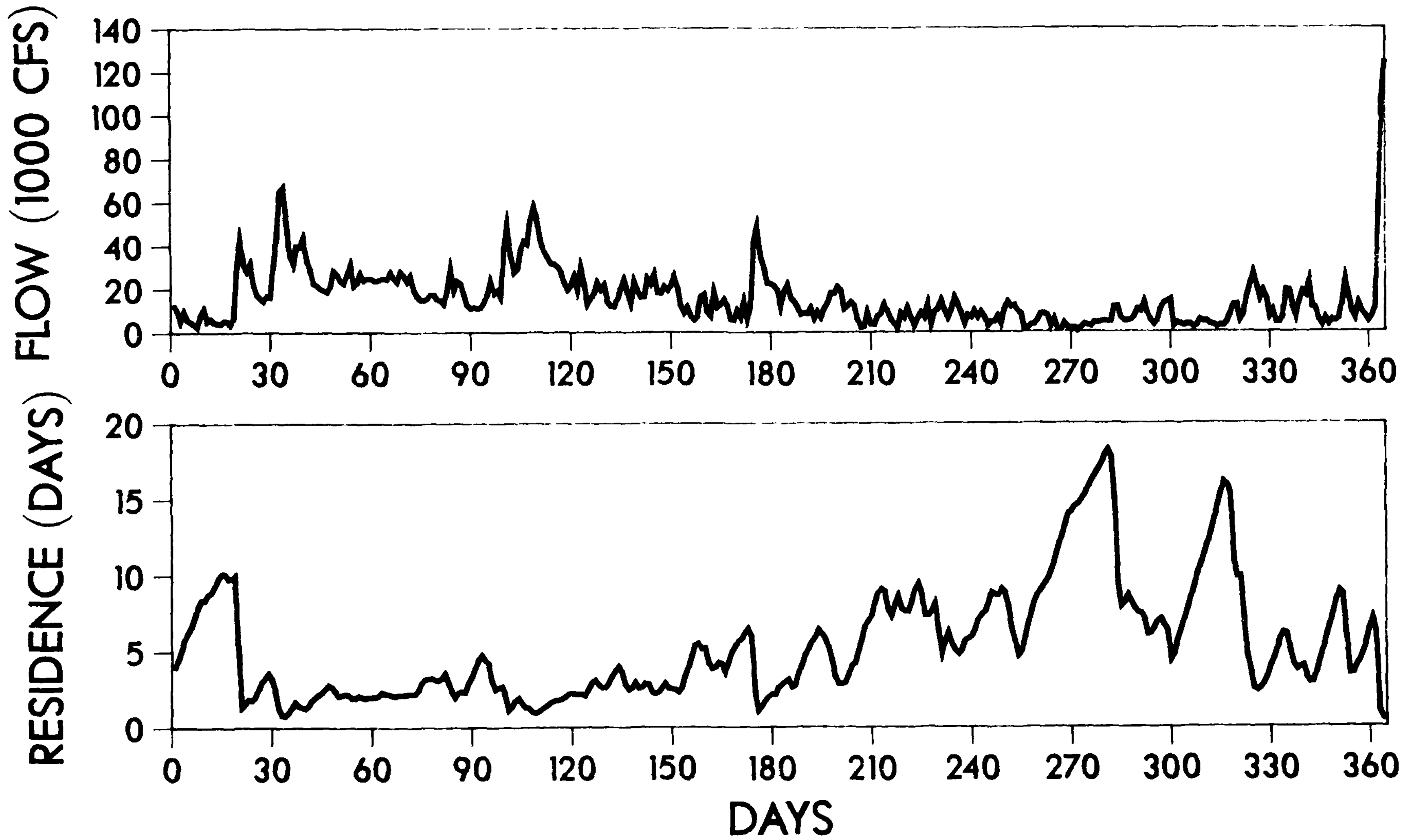


Figure AII-12

CHEATHAM RESERVOIR 1970

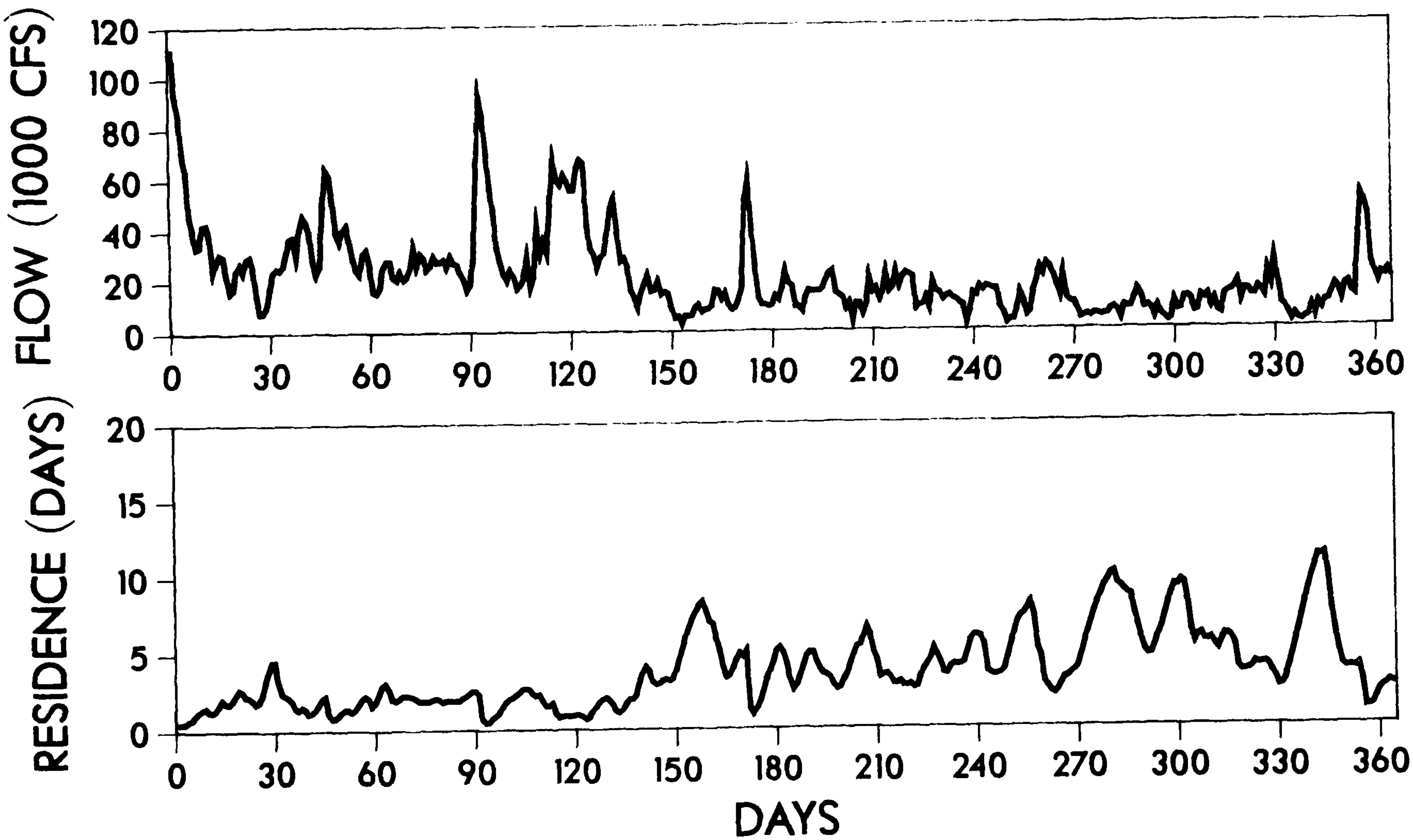


Figure AII-13

CHEATHAM RESERVOIR 1971

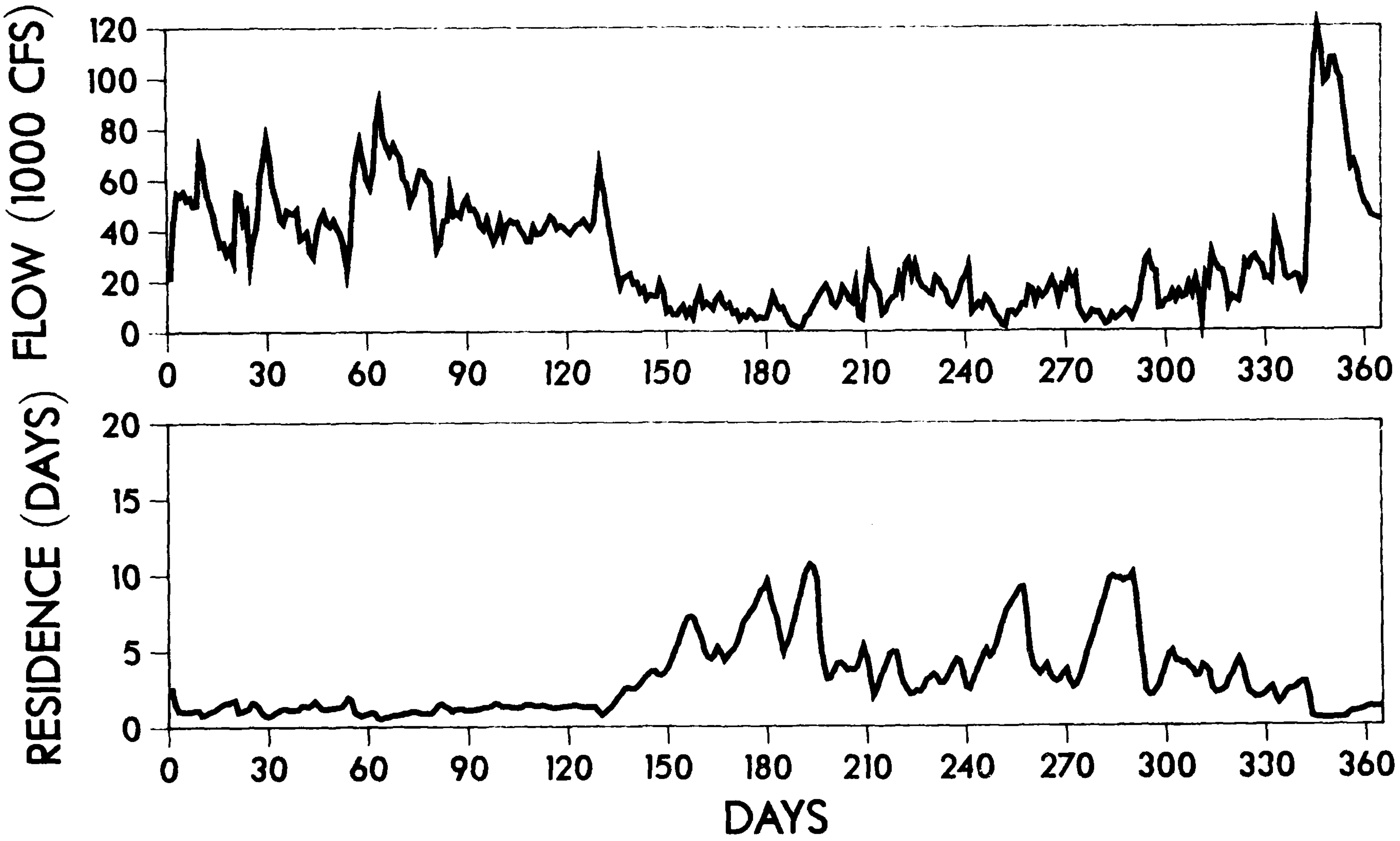


Figure AII-14

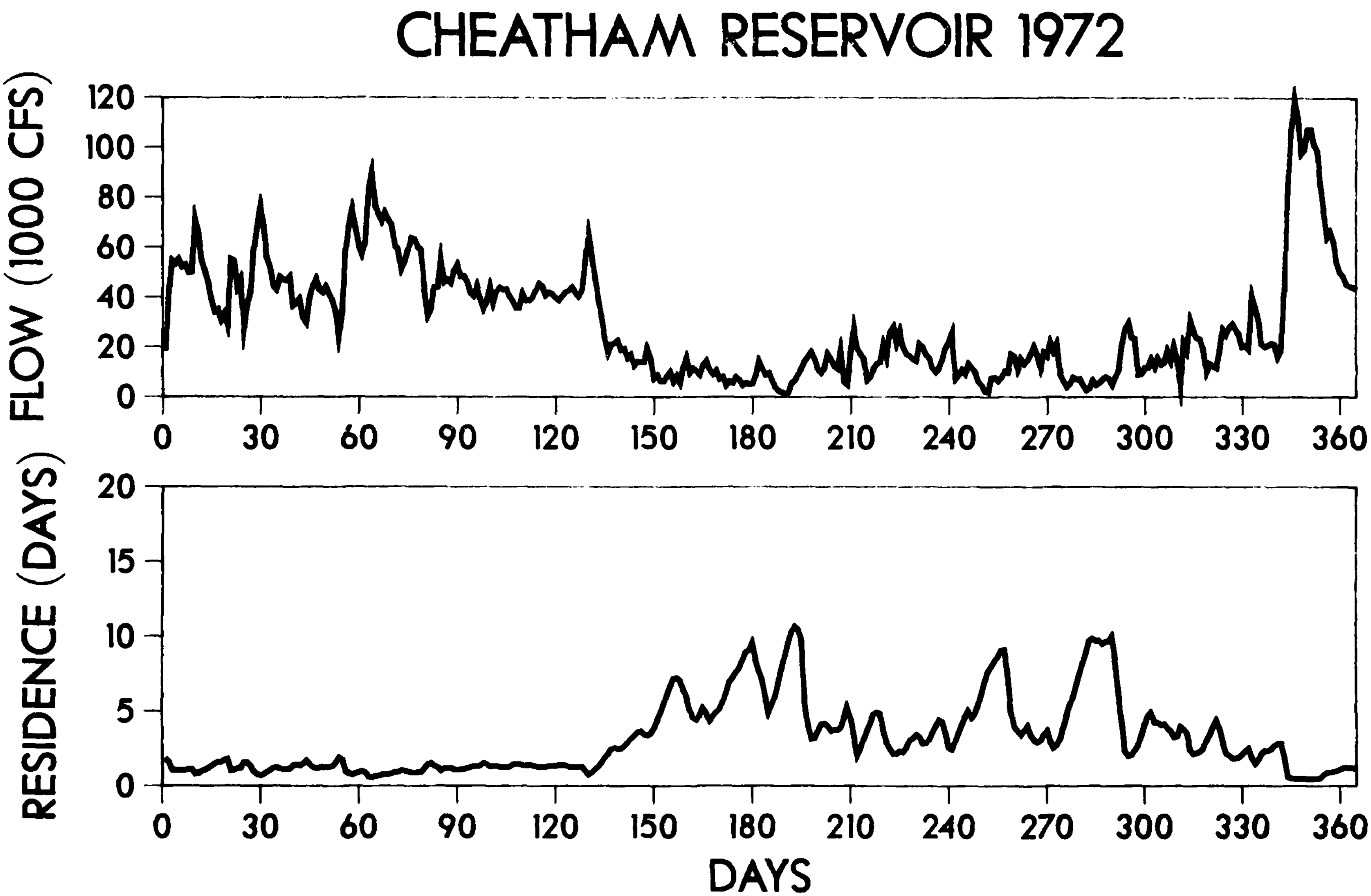


Figure AII-15

CHEATHAM RESERVOIR 1973

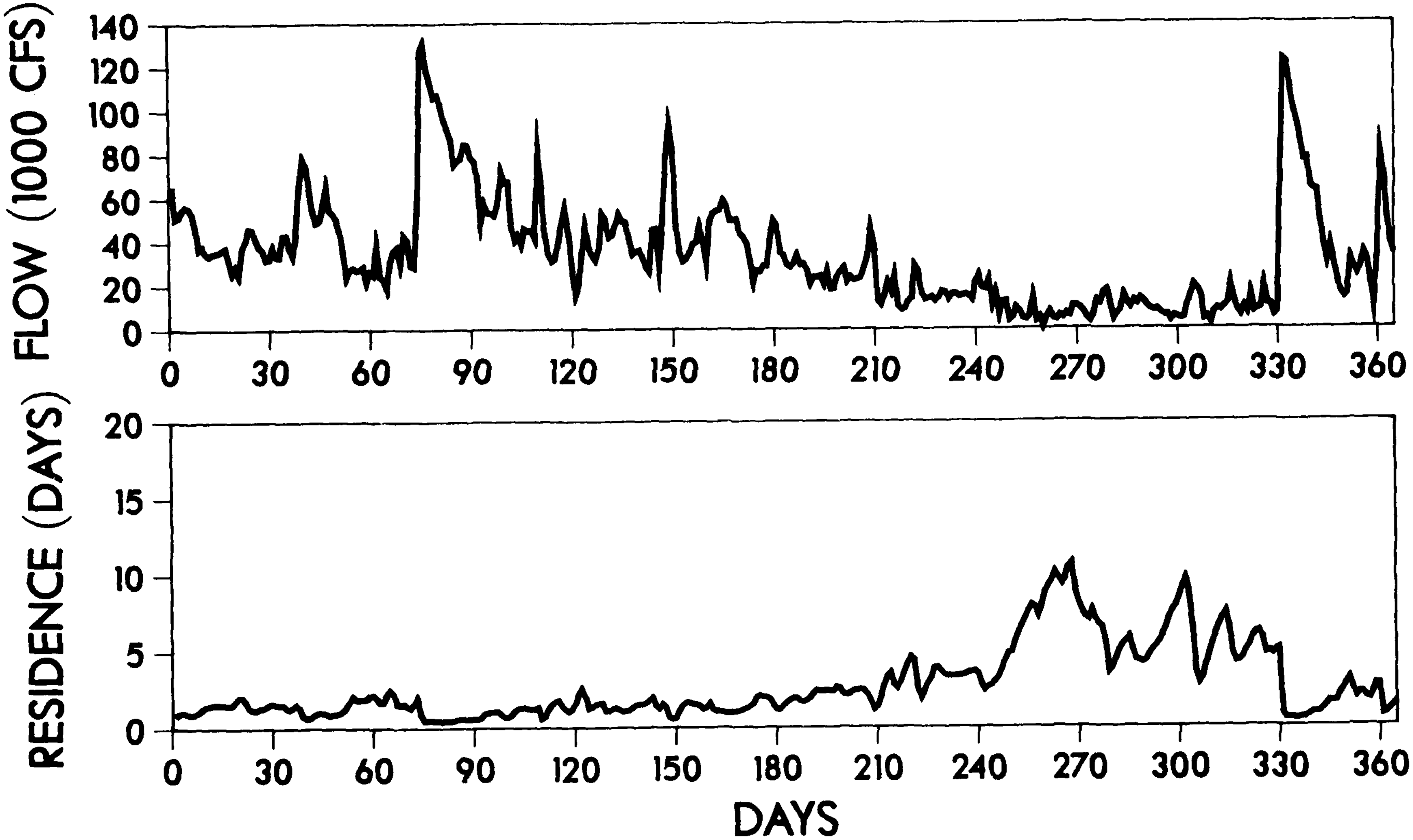


Figure AII-16

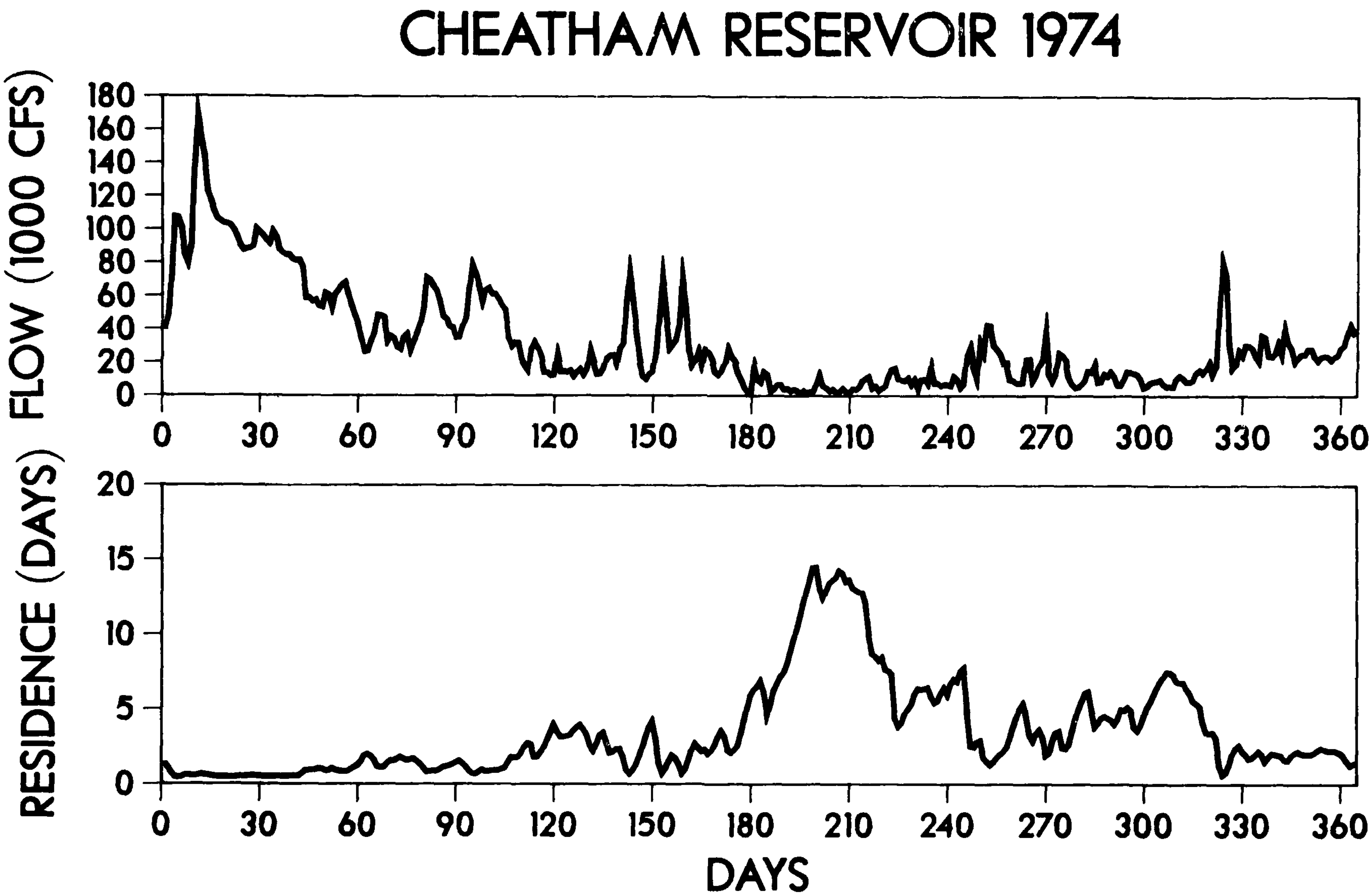


Figure AII-17

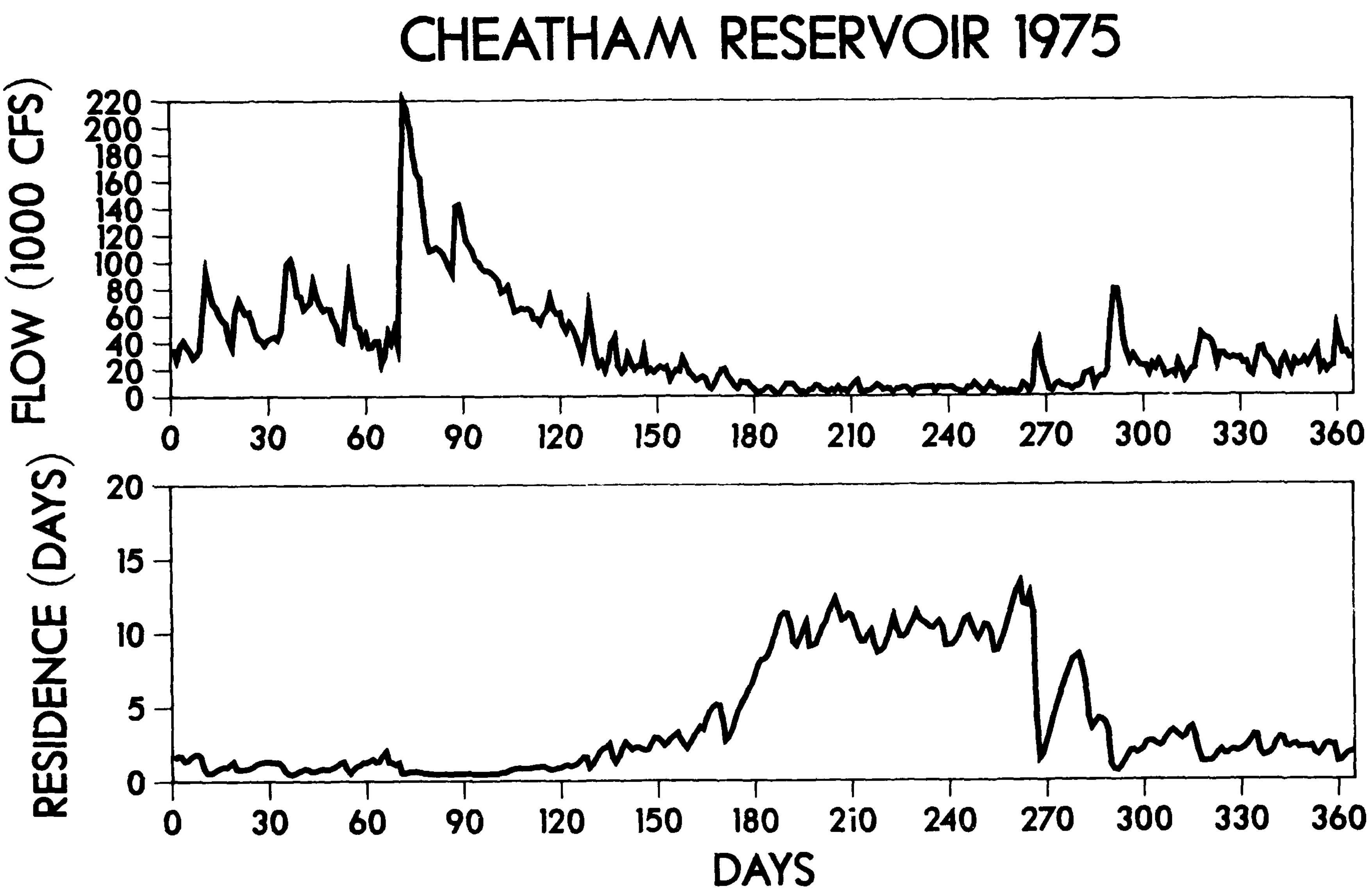


Figure AII-18

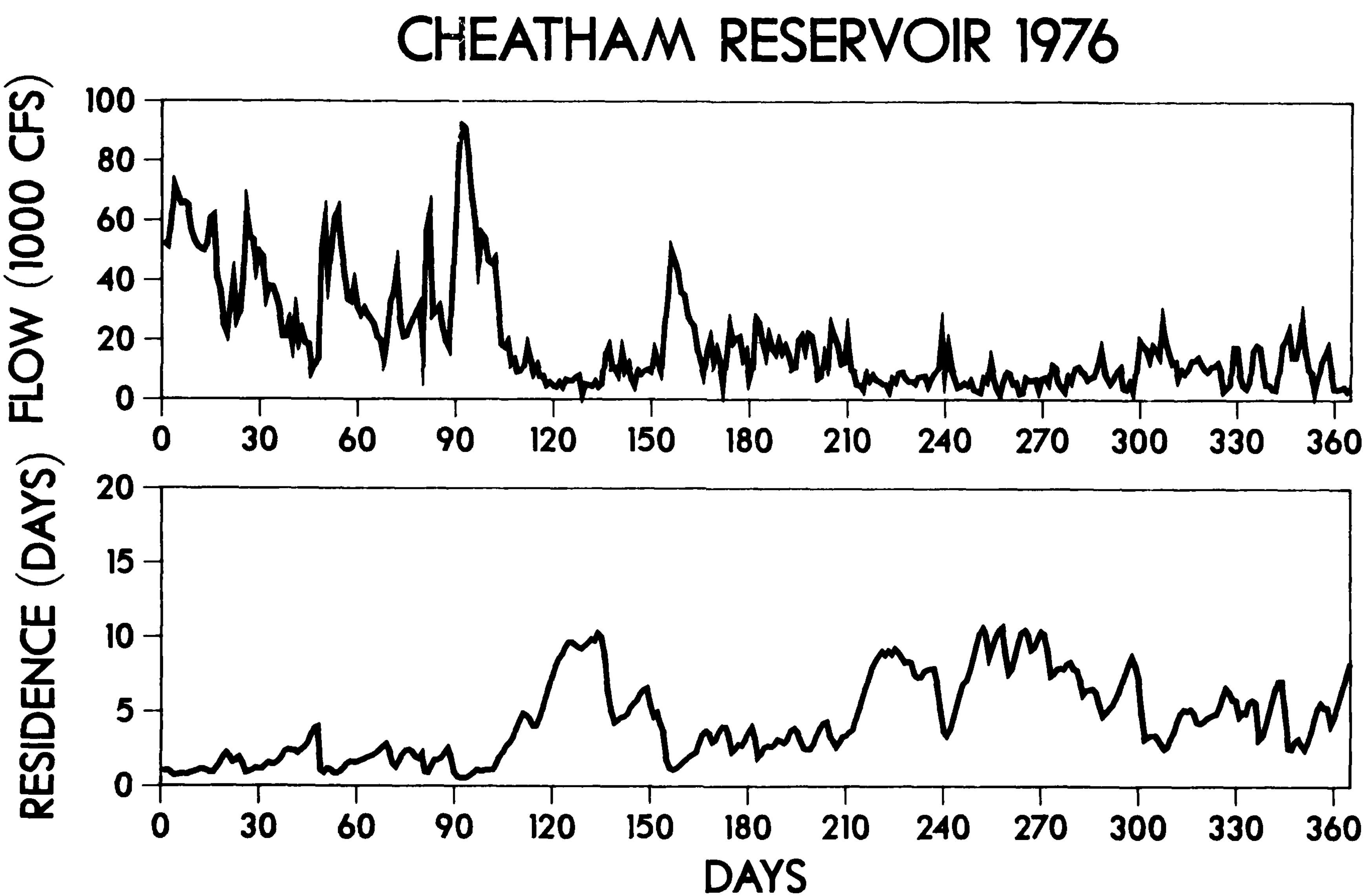


Figure AII-19

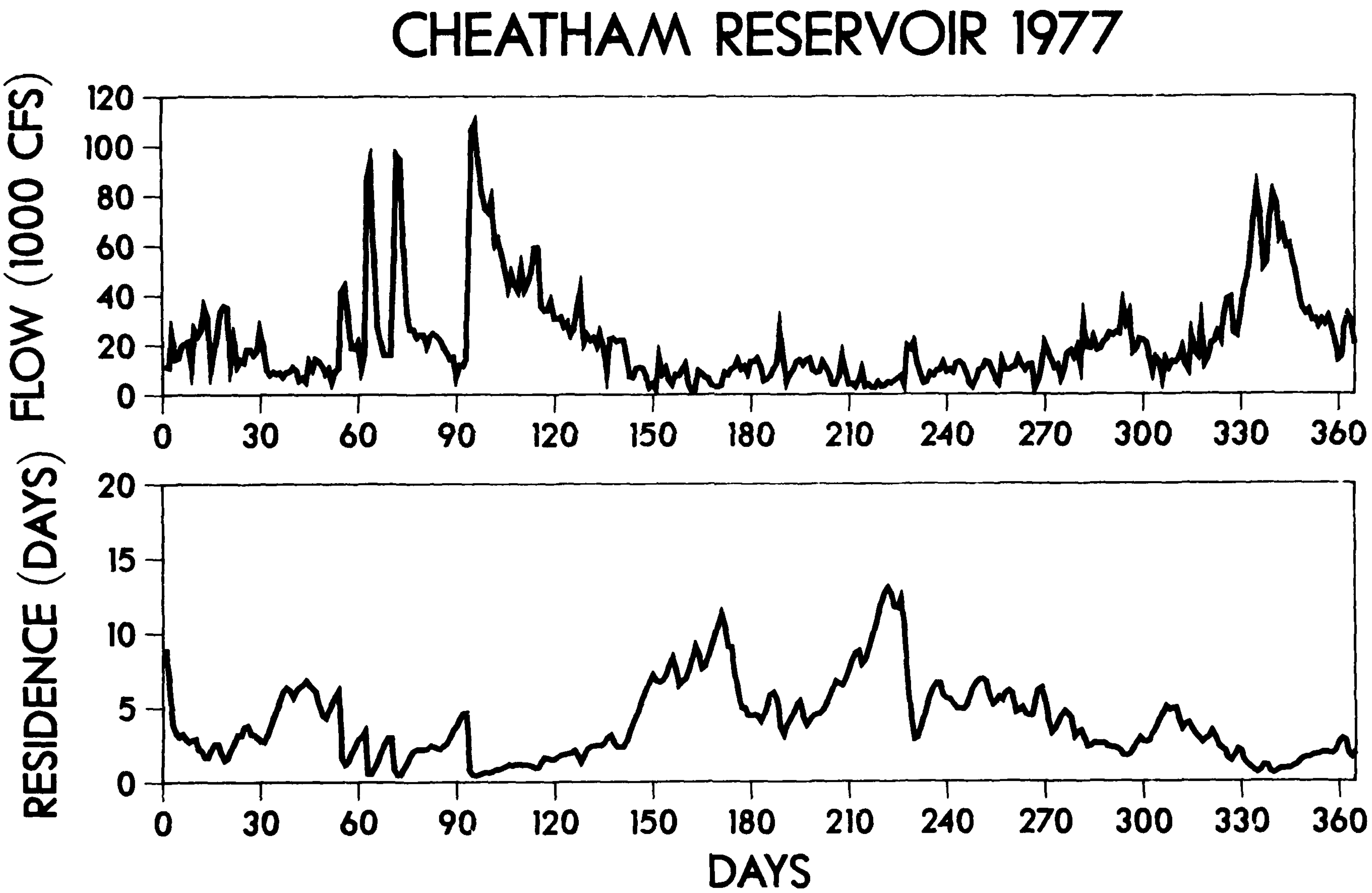


Figure AII-20

CHEATHAM RESERVOIR 1978

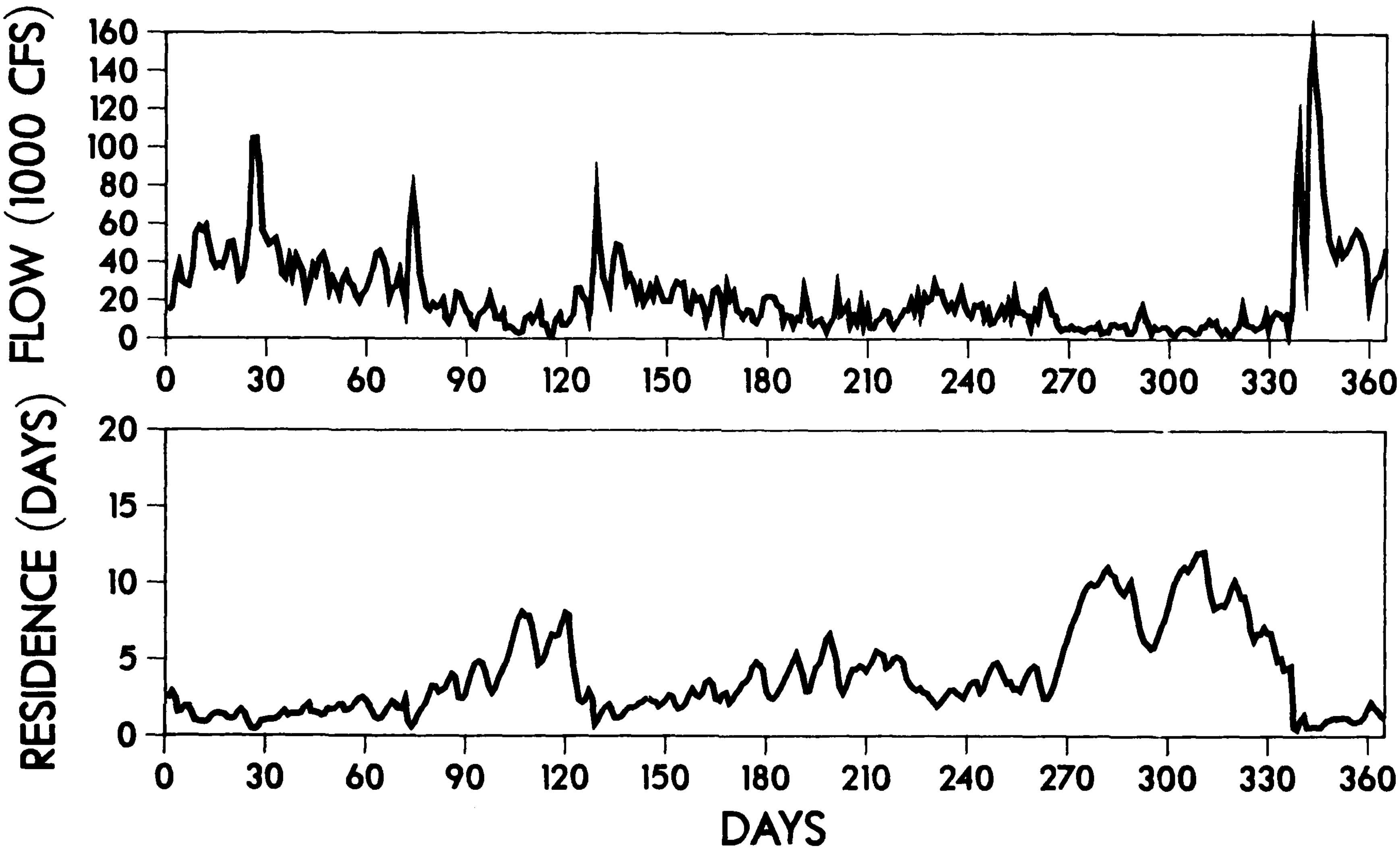


Figure AII-21

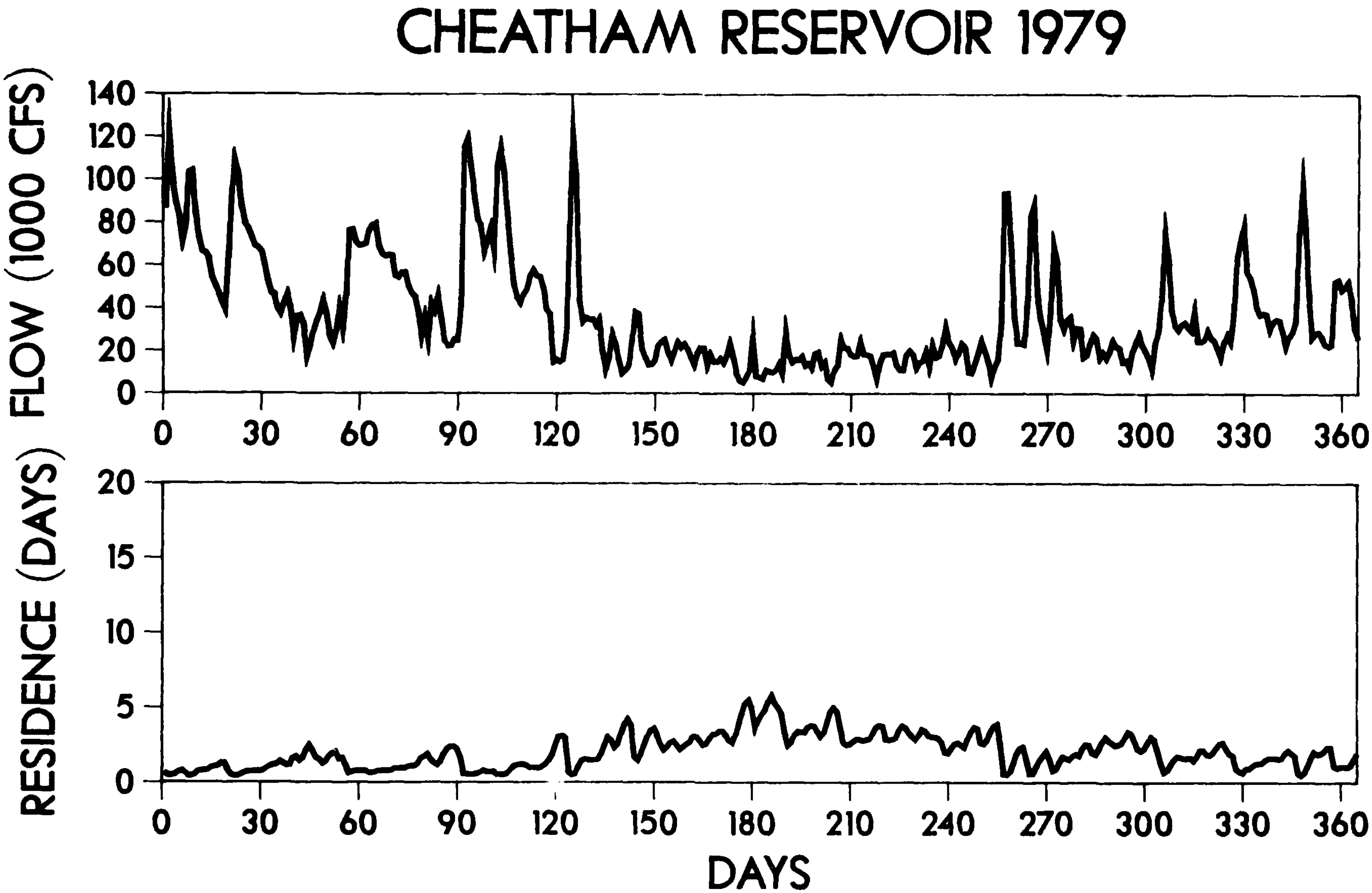


Figure AII-22

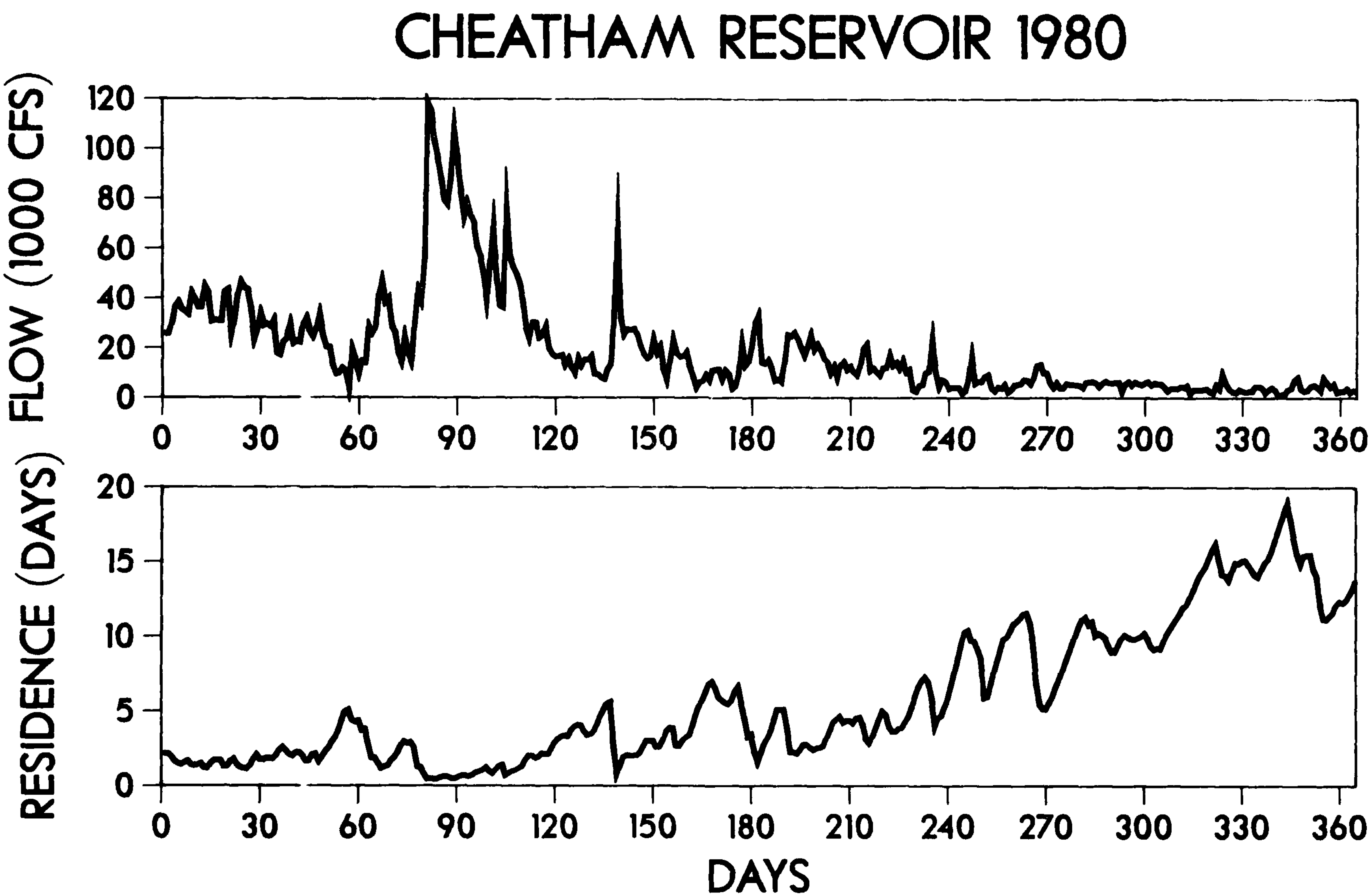


Figure AII-23

CHEATHAM RESERVOIR 1981

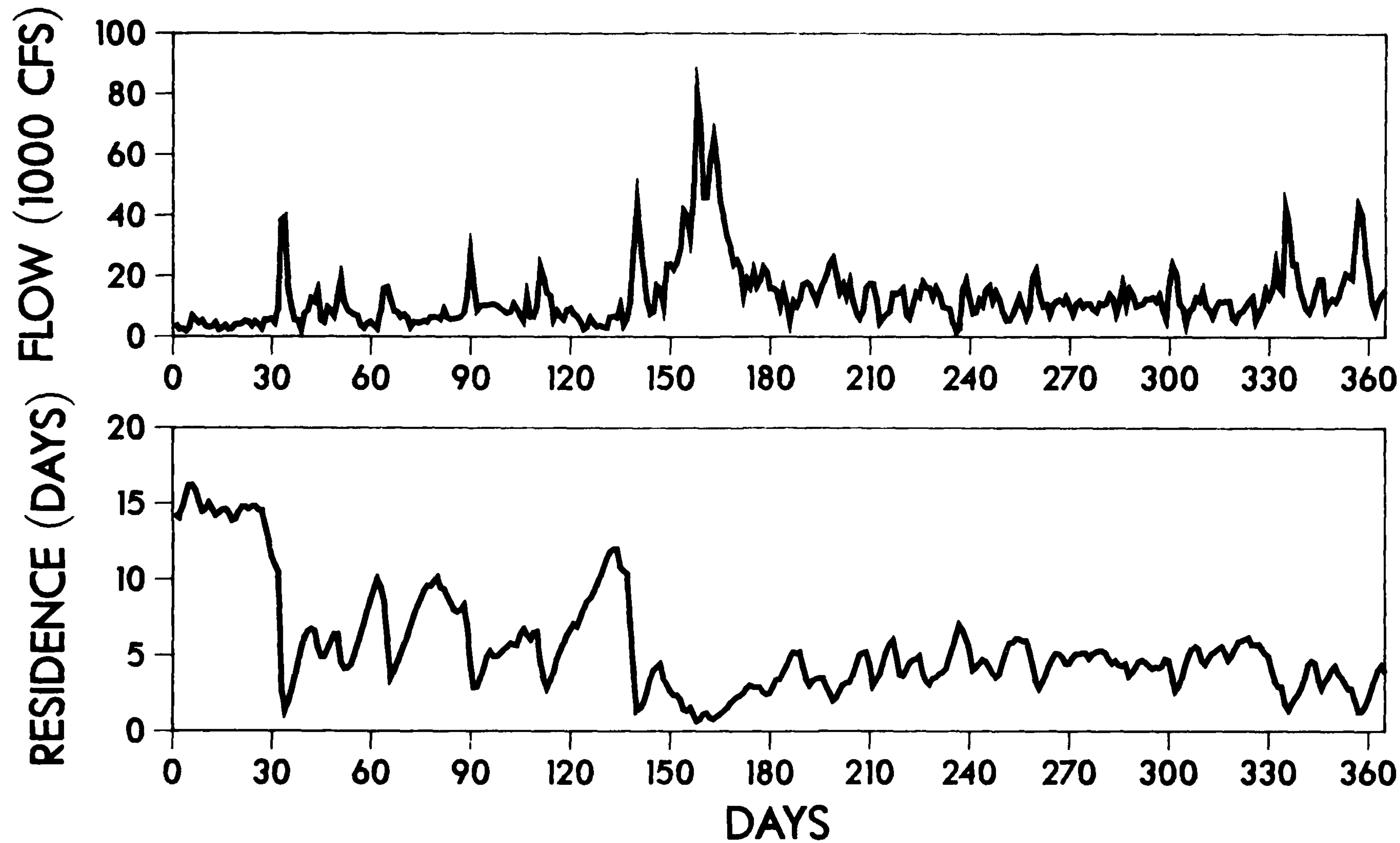


Figure AII-24

CHEATHAM RESERVOIR 1982

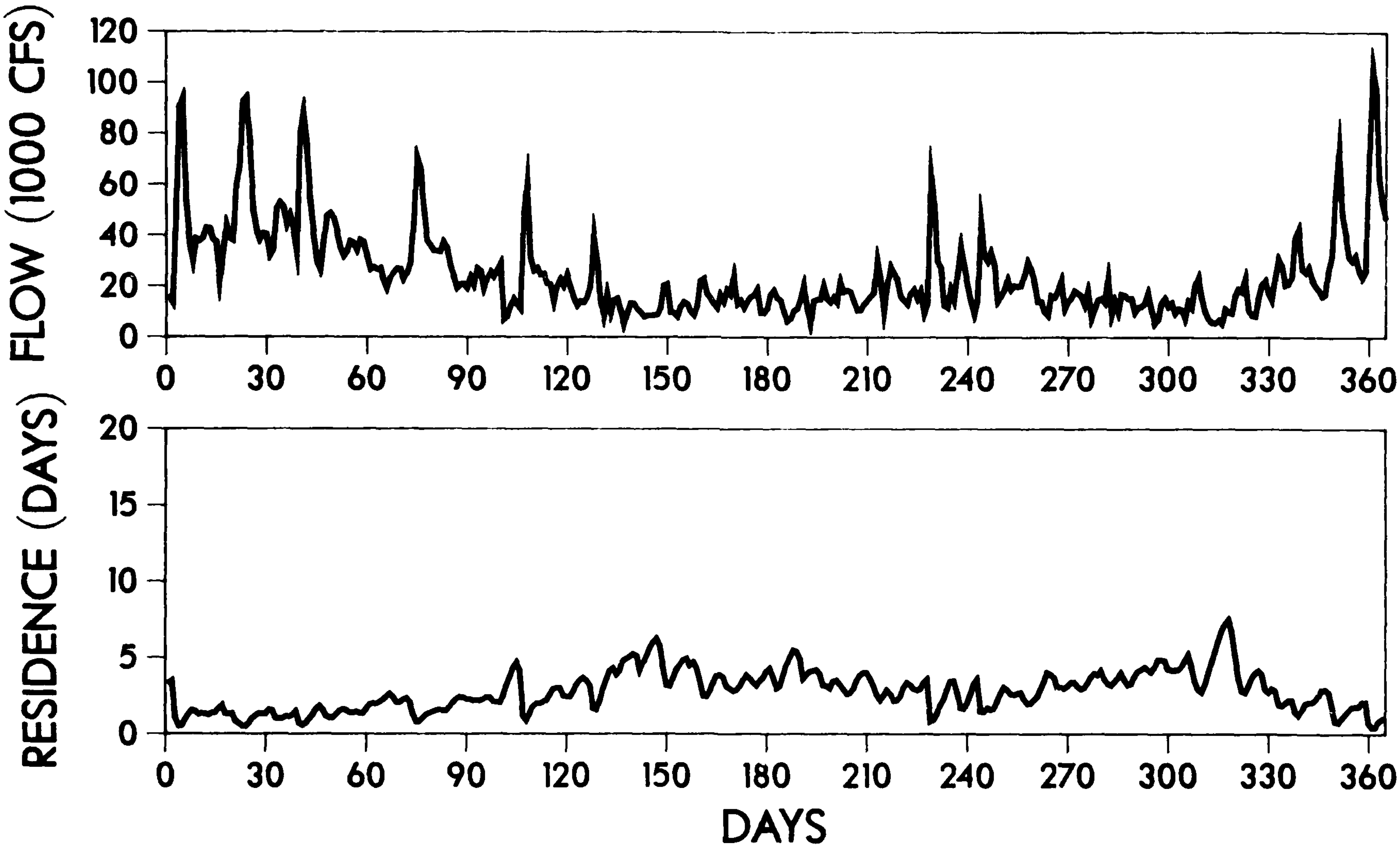


Figure AII-25

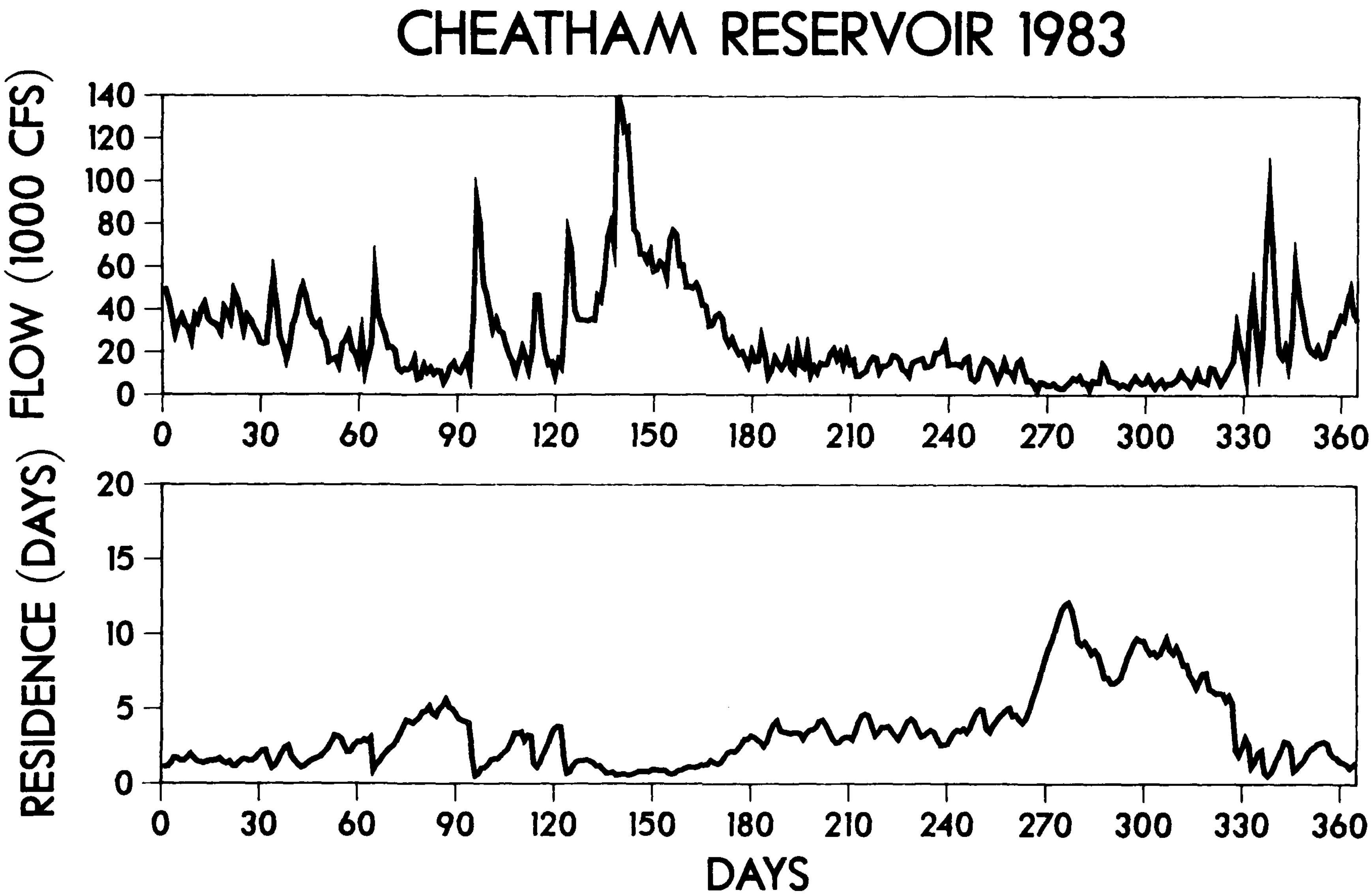


Figure AII-26

CHEATHAM RESERVOIR 1984

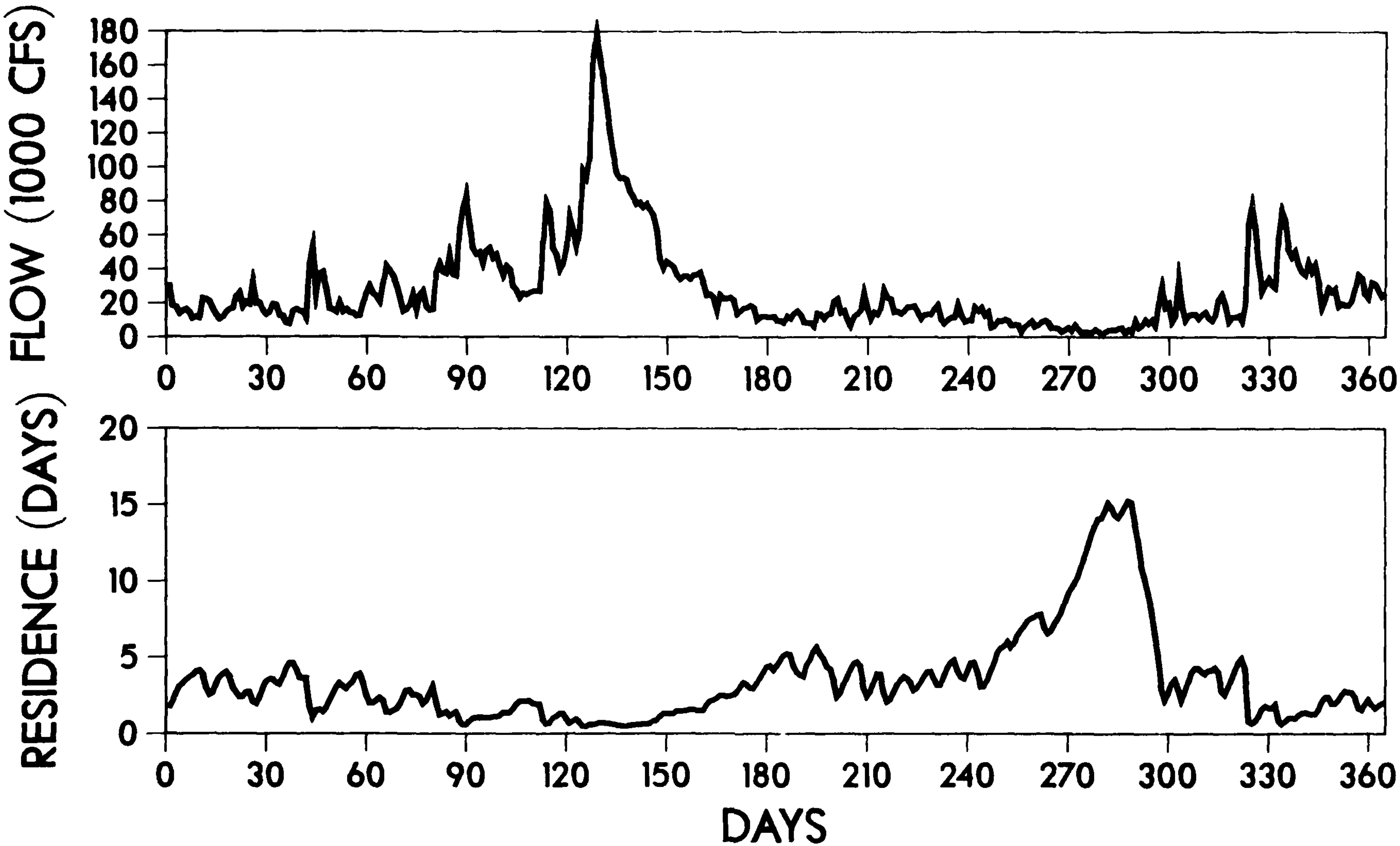


Figure AII-27

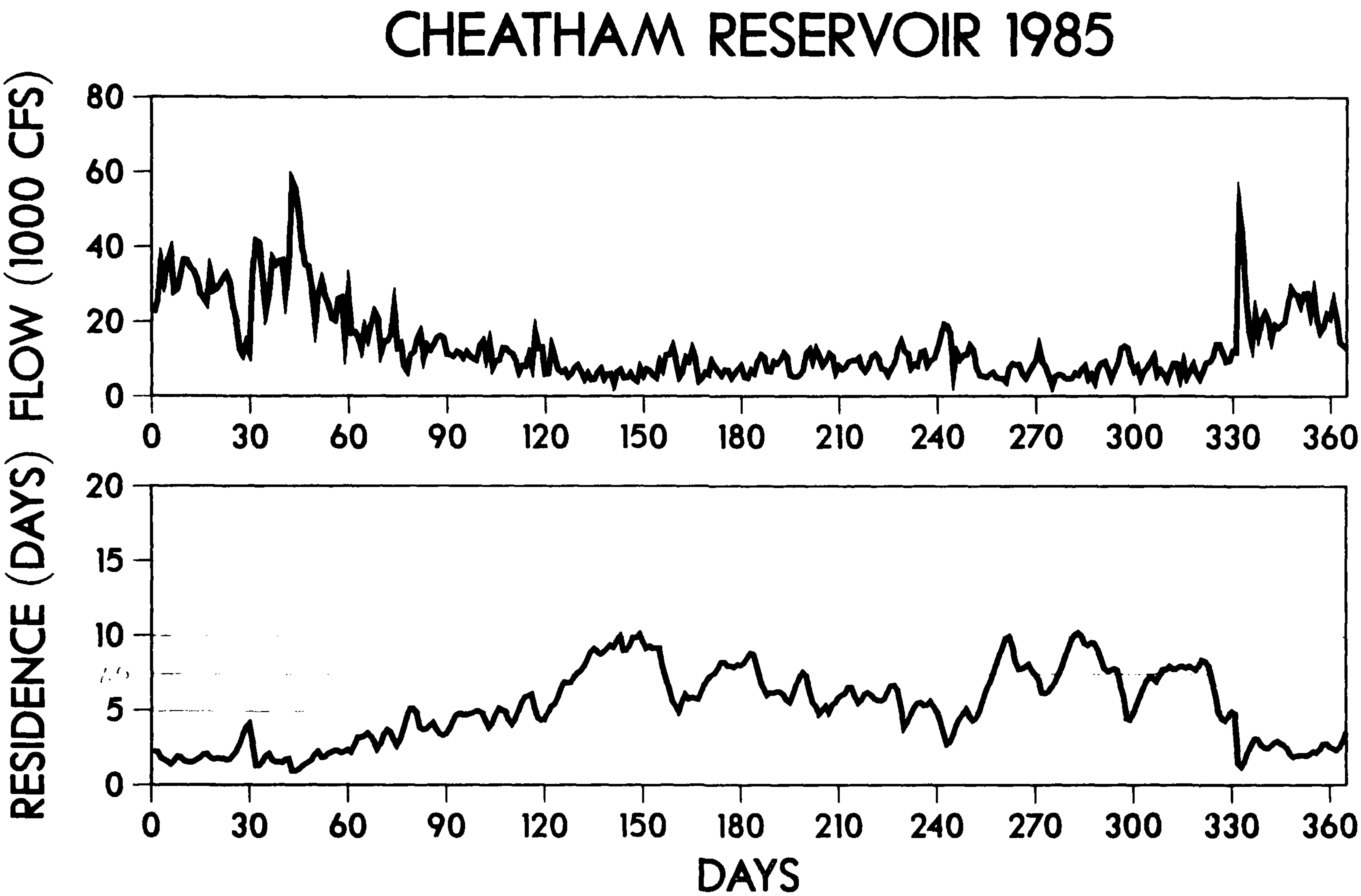


Figure AII-28

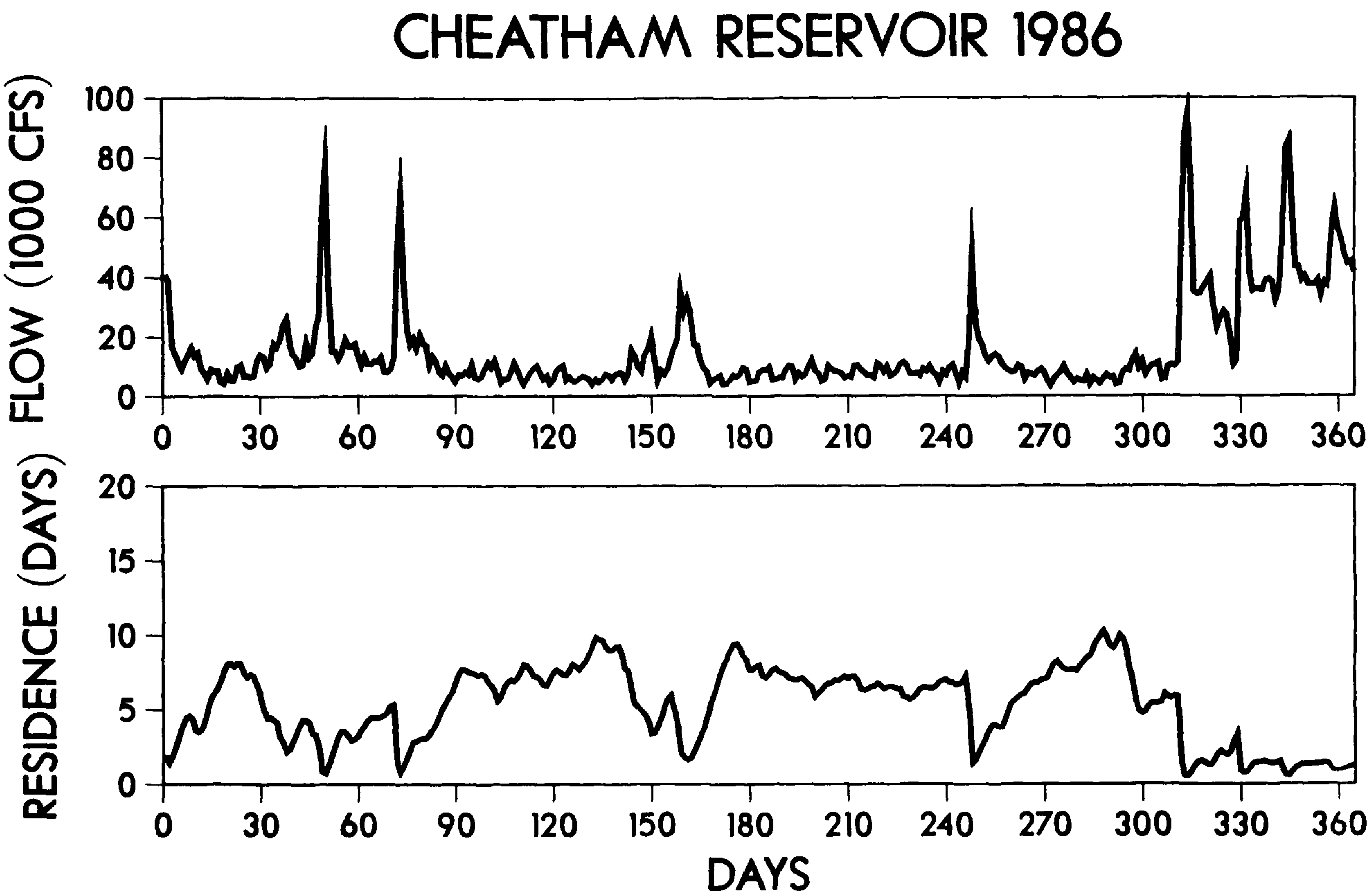


Figure AII-29

CHEATHAM RESERVOIR 1987